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Effect of Acoustic Oscillations on the Burning of Carbon

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ABSTRACT

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This study is concerned with the investigation of the effect of oscillatory flow on the burning of carbon. This involves the study of two separate problems. The first is to obtain a solution for combustion of a carbon particle surrounded by a stationary gaseous film, and the second is to obtain a solution for combustion of the carbon particle subjected to acoustic oscillations. A computer program is developed to solve the governing equations of both problems. Comparison of the solutions to the steady and the oscillatory cases provides information on the effect of the oscillations on carbon particle combustion.

Various plots are obtained from the computer generated results depicting the variation of parameters such as mass fractions of the species, pressure, temperature, and velocity across the boundary layer. The results obtained show that the oscillations interact positively with the combustion process, leading to an increase in the amplitude of the acoustic wave.

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NOMENCLATURE

u_x : velocity of flow in x-direction

u_y : velocity of flow in y-direction

P : pressure

ρ : density

μ : viscosity

T : temperature

$(\bar{\ })$: mean flow quantity

$(\ )_f$: fluctuating flow quantity

i : square root of negative one

ω : angular frequency

Y : mass fraction of ith species

Δh : change in enthalpy

RR : reaction rate

C_p : specific heat

λ : thermal conductivity

γ : ratio of specific heats

$\tilde{Y}$: admittance

V_x : diffusional velocity in x-direction

V_y : diffusional velocity in y-direction

D : diffusion coefficient

R_1, R_2 : rates of heterogeneous reactions

M_1, M_2, M_3 : molecular weights

a : sonic velocity

1.0 INTRODUCTION

The burning of a carbon particle is dependent upon the temperature, pressure, composition of the environment of the particle, as well as the particle size. The purpose of this study is to investigate whether carbon (graphite) subjected to oscillatory flow results in more complete combustion i.e. the reactants are more completely converted into products. The effect of particle structure on the burning process is neglected in this study. One possible approach to achieve more complete combustion is by increasing the temperature. However, this could result in dissociation as well as reactions involving nitrogen and oxygen (both of which are present in the ambient air), resulting in the formation of undesirable nitrogen oxides. An alternative approach, which is employed in this investigation, is to subject the particle to acoustic oscillations. This approach does not involve an increase in temperature, however conceivably promoting the combustion process through increased heat transfer and improved convection of species. As the carbon particle reacts with the atmosphere, burnt gases envelope it resulting in less oxygen available for the reaction. It is speculated that acoustic oscillations will tend to "sweep away" some of the burnt gases from the immediate surroundings of the carbon leading to improved convection.

An advantage of more complete carbon combustion is in the area of pollution control. Emission of carbon-monoxide (CO) from gas turbine engines is particularly high during idle and taxi operations (Jones,1978). The level of CO emissions can possibly be reduced by the proposed process of subjecting the combustion process to flow oscillations.

The combustion of carbon has been the focus of considerable research because it is present in all hydrocarbon fuels. Significant research has been done in modeling the diffusion and reaction in a stagnant boundary layer about a carbon particle. Two basic models have been proposed: Nusselt (1924) proposed a single film model which assumes that the oxidation of carbon is controlled by the diffusion of oxygen through a stationary film to the surface of the carbon particle where it reacts to form carbon dioxide (CO_2) and carbon monoxide (CO). Burke (1931) proposed the double film model in which the carbon reacts with CO_2, and the CO produced reacts further to form CO_2 in a thin flame front in the gas phase.

Several researchers have considered the dynamic behavior of a single carbon particle in an oxidizing ambient. Caram (1977) considers both spherical and flat carbon particles. Caram's model accounts for the homogeneous combustion of CO and the heterogeneous reaction of carbon with both oxygen and CO_2.

The model does not consider radiation and only accounts for independent diffusion. The paper presented the solution of the governing equations and depicts various parametric studies. It was shown that there exist multiple steady states. Libby (1979) conducted a more detailed study of the same problem. Libby investigated both frozen and equilibrium gas chemistries. Comparison of the solution was made with experimental results and previous theoretical studies. Mon (1978) continued the approach stated in Caram's research and generalized the problem to include multi-component diffusion and radiation.

Mon (1979) studied the stability of the steady states found by Caram (1977). He developed local asymptotic stability criteria for analysis of multiple steady states . The problem was further simplified by assuming the surrounding gas phase boundary layer was in a quasi-steady state. The numerical solution revealed the history of the particle burning from ignition to extinction.

Musarra (1985) developed a computer model to depict heat and mass transfer in the thermal boundary layer of a coal particle surrounded by a laminar gas stream at Sandia National Laboratories. This study was a result of the need for improved modeling of the devolatilization process in coal combustors. The solution of the time dependent governing equations utilizes a gridding scheme in order to provide grid resolution in the homogeneous reaction zone. Simulations showed that the CO produced during char oxidation is consumed in a thin reaction zone located nearly a diameter from the particle surface.

Sotirchos (1984) and Ballal (1989) modeled the transient combustion of porous char particles. Sotirchos's model revealed strong effects of the intraparticle thermal gradients and of the effect of the pore structure evolution scheme on the burning time. It predicted an optimum particle size that gives minimum burning time. The model is used primarily to study the effects of intraparticle thermal gradients on the solution structure in conjunction with the intraparticle diffusional limitations. Ballal developed a comprehensive mathematical model to predict the gasification behavior of coal-derived char particles when reacted with a gaseous mixture containing seven species of known temperature and composition. Predictions were made of ignition and quenching phenomena at the reaction conditions of interest.

More recently, Morell (1990) employed a diffusion - reaction model to investigate the pseudo-steady state and dynamic behavior of a single retorted shale particle exposed to a multi-component gaseous mixture. Among the parametric studies conducted are the effect on the combustion behavior of particle size, ambient temperature and pressure .

All of these investigations provided data on the various characteristics of burning of a solid in a stagnant atmosphere. Caram's study, in particular, is used to verify results obtained for the first part of this study; that is, the burning of carbon in a stagnant atmosphere. However, relatively little research has been conducted in the area of combustion characteristics of carbon subjected to oscillatory flow. This study is an effort to contribute to this field.

The following discussion outlines the method that is used to investigate the effect of acoustic oscillations on the burning of carbon. First, the governing equations for the carbon in stagnant flow conditions are developed. Next, the governing equations are modified to include the carbon being subjected to oscillatory flow. A computer program is developed to solve these systems of equations and is used to investigate the influence of oscillations on carbon burning.

2.0 METHOD

In order to study the effect of acoustic oscillations on the reactions in the thermal boundary layer of a carbon particle, two separate problems will be considered. The first is to obtain a solution for a carbon particle surrounded by a stationary gaseous film and the second is to obtain a solution for the carbon particle subjected to oscillations. The results will indicate whether the oscillations interact with the combustion process in a positive manner. The following assumptions are made for modeling the problem under investigation:

a) Carbon has the shape of a flat slab.(See Figure 1.0)

b) Carbon is impervious to diffusion.

c) Nitrogen is considered chemically inert.

d) Fluid is Newtonian.

e) Fluid has constant density and viscosity.

f) Body forces are neglected.

g) Fluid has constant specific heat and thermal conductivity.

h) Effect of radiation is neglected.

i) Dufour effect is neglected.

j) Dissipation of viscous stresses is negligible.

k) Fluid properties are constant in the x-direction.

It is realized that radiation could make significant contribution

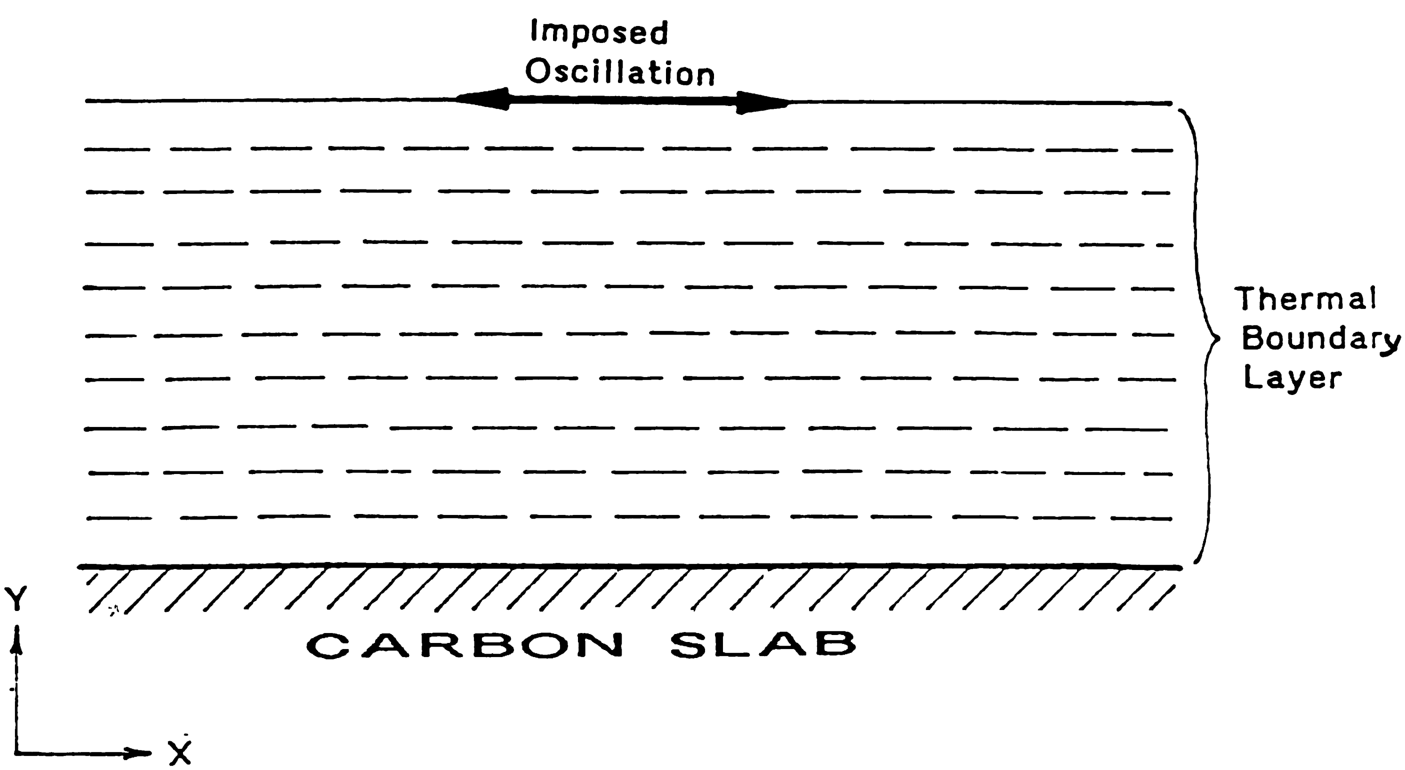

Figure 1: Model under investigation

to the physical process under study. For instance, Mon (1978) concluded that radiation completely altered the qualitative nature of the combustion process of a large single particle in a stagnant boundary layer. However, due to the attendant complexities its effect has been ignored in this analysis.

Chemical species that are typically present in the gas phase are CO_2, CO, and O_2. The following equilibrium stoichiometric reactions are considered to be the more significant ones (Glassman,1977) :

a) The heterogeneous reactions at the carbon surface :

$$2C + O_2 = 2CO$$

$$C + CO_2 = 2CO$$

b) The homogeneous reaction in the boundary layer :

$$CO + \frac{1}{2}O_2 = CO_2$$

The conservation equations for species , mass continuity , momentum, and energy can be written as follows :

SPECIES :

$$\rho\left[\frac{\partial Y_i}{\partial t}+u_x\frac{\partial Y_i}{\partial x}+u_y\frac{\partial Y_i}{\partial y}\right]+\frac{\partial}{\partial x}[\rho Y_i V_{i_x}]+\frac{\partial}{\partial y}[\rho Y V_{i_y}]=RR_i \tag{2-1}$$

where i=1,2,3.

CONTINUITY :

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}[\rho u_x]+\frac{\partial}{\partial y}[\rho u_y]=0 \tag{2-2}$$

MOMENTUM :

$$\rho\left[\frac{\partial u_x}{\partial t}+u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}\right]=-\frac{\partial P}{\partial x}+\mu\left[\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}\right]$$

$$\rho\left[\frac{\partial u_y}{\partial t}+u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}\right]=-\frac{\partial P}{\partial y}+\mu\left[\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}\right] \tag{2-3}$$

ENERGY :

$$\rho C_p [\frac{\partial T}{\partial t}+u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}] - [\frac{\partial P}{\partial t}+u_x\frac{\partial P}{\partial x}+u_y\frac{\partial P}{\partial y}] = \lambda [\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}]$$
$$-\sum RR_i \Delta h_{f,i} - [\frac{\partial}{\partial x}[\rho T\sum C_{p_i}Y_i V_{i_x}] + \frac{\partial}{\partial y}[\rho T\sum C_{p_i}Y_i V_{i_y}]] \quad (2-4)$$

STAGNANT BOUNDARY LAYER

Considering a stagnant, steady state ambient about the carbon particle, the above governing equations in the y-direction reduce to:

SPECIES :

$$\frac{\partial}{\partial y}[\rho D_i \frac{\partial Y_i}{\partial y}] = -RR_i \quad (2-5)$$

Y-MOMENTUM :

$$\frac{dP}{dy}=0 \quad (2-6)$$

ENERGY :

$$\lambda \frac{\partial^2 T}{\partial y^2} = \sum RR_i \Delta h_{f,i} \quad (2-7)$$

At the carbon surface , the boundary conditions can be written as follows :

$$-\frac{\rho D_1}{M_1}\left[\frac{\partial Y_1}{\partial y}\right]_{y=0}=-R_2$$

$$-\frac{\rho D_2}{M_2}\left[\frac{\partial Y_2}{\partial y}\right]_{y=0}=2\left[R_1+R_2\right]$$

$$-\frac{\rho D_3}{M_3}\left[\frac{\partial Y_3}{\partial y}\right]_{y=0}=-R_1 \qquad (2-8)$$

$$-\lambda\left[\frac{\partial T}{\partial y}\right]_{y=0}=\left[-\Delta H_1\right]R_1+\left[-\Delta H_2\right]R_2$$

The above system of equations with the corresponding boundary conditions will be solved, using an existing variable step fourth order Runge - Kutta subroutine, on the mainframe computer (IBM 4361) .

OSCILLATING BOUNDARY LAYER

In order to obtain the unsteady system of equations due to oscillations, the governing equations have to be perturbed. To do this, the dependent variables in the governing equations are expressed as the sum of steady and unsteady parts :

$$\rho=\bar{\rho}+\rho' \qquad \rho'=\rho_f e^{i\omega t} \qquad T=\bar{T}+T' \qquad T'=T_f e^{i\omega t}$$

$$u=\bar{u}+u' \qquad u'=u_f e^{i\omega t} \qquad P=\bar{P}+P' \qquad P=P_f e^{i\omega t} \qquad (2-9)$$

Again quiescent conditions are assumed ($\bar{u} = \bar{v} = 0$). Linearizing the resulting equations, assuming sinusoidal oscillations of frequency ω , and separating into steady and unsteady parts yield the following steady-state equations :

SPECIES :

$$\frac{d}{dy}[\bar{\rho}\bar{Y}_i\bar{V}_{iy}] = RR_i \tag{2-10}$$

Y-MOMENTUM :

$$\frac{d}{dy}\bar{P}=0 \tag{2-11}$$

ENERGY :

$$\lambda\frac{d^2\bar{T}}{dy^2}-\sum\overline{RR_i}\Delta h_{f,i}-\frac{d}{dy}[[\bar{\rho}\bar{T}\sum C_{p_i}\bar{Y}_i\bar{V}_{i_y}]]=0 \tag{2-12}$$

and the following unsteady equations :

SPECIES :

$$D_i\overline{\rho}\frac{d^2 Y_{if}}{dy^2}=i\omega\overline{\rho}Y_{if}+\overline{\rho}u_{yf}\frac{d\overline{Y_i}}{dy}-\frac{d^2}{dy^2}[D_i\rho_f\overline{Y_i}] \tag{2-13}$$

CONTINUITY :

$$\frac{du_{yf}}{\partial y}=-\frac{i\omega\rho_f}{\overline{\rho}}-\frac{u_{yf}}{\overline{\rho}}\frac{d\overline{\rho}}{dy} \tag{2-14}$$

Y-MOMENTUM :

$$\overline{\rho}D\frac{d^2 u_{yf}}{dy^2}=i\omega\overline{\rho}u_{yf}+\frac{dP_f}{dy} \tag{2-15}$$

ENERGY :

$$\lambda\frac{d^2 T_f}{dy^2}-[\sum(RR_i)_f\Delta h]$$
$$=C_p[i\omega\overline{\rho}T_f+\overline{\rho}u_{yf}\frac{\partial\overline{T}}{\partial y}]-i\omega[\overline{\rho}RT_f+\rho_f R\overline{T}] \tag{2-16}$$

In order to solve the unsteady system of equations, an order of magnitude analysis is performed in an effort to simplify the equations. Such an analysis requires non-dimensionalizing the equations. The following parameters are defined :

$$P_f^* = \frac{P_f}{P_R} \qquad T^* = \frac{T_f}{T_R}$$

$$y^* = \frac{y}{a/\omega} \; where \rightarrow a = \left[\frac{\gamma P_R}{\rho_R}\right]^{1/2} \qquad (2\text{-}17)$$

$$u_{yf}^* = \frac{u_{yf}}{a}$$

Consequently, the non-dimensionalized equations become :

SPECIES :

$$\frac{d^2 Y_{if}}{dy^{2*}} = i\frac{\gamma P_R Y_{if}}{\rho_R D_i \omega} + \frac{\gamma P_R u_{yf}^*}{\rho_R D_i \omega} - \frac{\rho_R}{\bar{\rho}}\frac{d^2}{dy^{*2}}\rho_f^* \bar{Y}_i \qquad (2\text{-}18)$$

CONTINUITY :

$$\frac{d^2 u_{yf}^*}{dy^{*2}} = -i\frac{\rho_f^* \rho_R}{\bar{\rho}} - \frac{u_{yf}^*}{\bar{\rho}}\frac{d\bar{\rho}}{dy^*} \qquad (2\text{-}19)$$

Y-MOMENTUM :

$$\frac{d^2 u_{yf}}{dy^{*2}} = i\frac{\gamma P_R u_{yf}^*}{\rho_R D\omega} + \frac{P_R}{\bar{\rho} D\omega}\frac{dP_f^*}{dy^*} \qquad (2\text{-}20)$$

ENERGY :
$$\frac{d^2T^*}{dy^{*2}}=\frac{\gamma P_R}{\rho_R\lambda T_R\omega^2}[\sum (RR_i)_f\Delta h]+i\frac{\gamma P_R}{\rho_R D\omega}T^*+\frac{\gamma P_R}{\rho_R D\omega}u_{yf}^*\frac{d\overline{T}^*}{dy^*}-$$
$$i\frac{R\gamma P_R}{\rho_R DC_p\omega}T^*-i\frac{R\gamma P_R}{\overline{\rho}DC_p\omega}\rho_f^* \qquad (2\text{-}21)$$

Considering typical values of the various parameters lead to the following simplifications : Terms 1, 4, 6, 8 can be neglected due to relatively small order of magnitude in their respective equations. Consequently, the final unsteady equations are as follows :

SPECIES :
$$i\omega\overline{\rho}Y_{if}+\overline{\rho}u_{yf}\frac{d\overline{Y_i}}{dy}=0 \qquad (2\text{-}22)$$

CONTINUITY :
$$\frac{du_{yf}}{dy}=-\frac{u_{yf}}{\overline{\rho}}\frac{d\overline{\rho}}{dy} \qquad (2\text{-}23)$$

Y-MOMENTUM :
$$0=i\omega\overline{\rho}u_{yf}+\frac{dP_f}{dy} \qquad (2\text{-}24)$$

ENERGY :
$$\lambda\frac{d^2T_f}{dy^2}-[\sum (RR_i)_f\Delta h]$$
$$=C_p[i\omega\overline{\rho}T_f+\overline{\rho}u_{yf}\frac{\partial\overline{T}}{\partial y}]-i\omega[\overline{\rho}RT_f+\rho_fR\overline{T}] \qquad (2\text{-}25)$$

For a complete documentation of the order of magnitude analysis, the reader is referred to Appendix C.

Examination of the simplified unsteady equations shows that they are dependent upon the steady state solution. It must also be noted that they are a system of linear, ordinary coupled differential equations that can be solved using the Runge-Kutta scheme in conjunction with the steady state equations. The output of the program contains two separate sets of results : one for the steady-state solution and the other for the unsteady-state solution. The results provide the necessary information to show whether the acoustic oscillations are interacting with the combustion process in a positive manner.

3.0 DESCRIPTION OF COMPUTER PROGRAM

The computer program developed consists of two major sections that deal with the solution of the steady equations and unsteady equations.

The steady equations (2-5) to (2-7) and the corresponding boundary conditions (2-8) are transformed into one differential equation and a set of algebraic equations. This is accomplished by using the technique specified by Caram (1977). This technique is described in Appendix A. The method simplifies the numerical solution since only one differential equation needs to be solved. The original system of equations consisted of four simultaneous differential equations and consequently convergence to the desired solution is more difficult. These new transformed equations compose the first part of the program. The subroutine FCN defines the differential equation. In order to solve the differential equation a fourth-order variable-step Runge-Kutta subroutine RKINIT is invoked. This scheme obtains error estimates and fifth order accuracy by solving the system at two different step lengths. Consequently, this requires 5.5 function evaluations per step, as compared with 6 in an ordinary fifth order method.

The unsteady equations (2-22) to (2-25) form the second part of the computer program. They constitute a set of differential equations that are also solved using subroutine FCN.

The listing of the computer program is included in the Appendix E. The various final equations that were incorporated into the computer program are shown in Appendix B.

4.0 DISCUSSION OF RESULTS

The results of this investigation are presented in Figures 2 to 9. These figures contain the profiles of the various parameters across the boundary layer of the carbon.

In order to obtain the various flow properties at each step across the boundary layer distance, the program developed obviously requires various boundary conditions and input parameters. The imposed conditions on the model under investigation are as follows :

(i) Steady temperature at carbon surface = 1171 K

(ii) Steady mass fraction of CO_2 at boundary = 0.0

(iii) Steady mass fraction of CO at boundary = 0.0

(iv) Steady mass fraction of O_2 at boundary = 10% by volume O_2 = 0.1126

(v) Boundary layer thickness = 5.0 mm

(vi) Step size = 0.1

The unsteady temperature, unsteady pressure, and the frequency of oscillation are input parameters and are varied to obtain different profiles.

Figure 2 depicts the variation of the three mass fractions (CO_2,CO,O_2) with the non-dimensional boundary layer distance. The oxygen mass fraction increases almost linearly from the carbon surface to the edge of the boundary layer. The mass fraction of carbon-monoxide decreases from its initial value at the surface to zero at the boundary. This decrease is quite rapid in the first three-tenths of the boundary layer distance, and it tapers off for the rest of the distance. The carbon-dioxide mass fraction shows an initial increase (for about one-tenth of the distance) followed by an almost linearly decreasing variation. As required, there is no CO_2 at the edge of the boundary layer. This plot suggests that the oxidation of carbon is controlled by diffusion of oxygen from the ambient to the surface of the carbon where it reacts to form CO and CO_2. The change of slope of the mass fraction of carbon-dioxide suggests that at about one-tenth of the boundary layer distance there is a thin flame front.

Figure 3 shows the variation of the temperature with the boundary layer distance. As expected, the temperature is maximum at the carbon surface and it decreases to the ambient temperature at the edge of the boundary layer.

Figure 4 shows that the unsteady velocity component in the y-direction decreases with the boundary layer distance. The two curves shown correspond to two different unsteady surface temperatures. It is observed that at the higher unsteady surface temperature, the unsteady velocity decreases more rapidly with distance.

Figure 5 depicts a linear increase in the magnitude of the unsteady temperature with the boundary layer distance. It can also be noted from the plot that a higher unsteady surface temperature leads to a more rapid increase in the unsteady temperature across the boundary layer.

Figure 6 corresponds to the relationship between the phase angle of the unsteady temperature and the boundary layer distance. It can be observed that the rate of increase of phase angle goes up with boundary layer distance.

Figure 7 shows the variation of the unsteady mass fractions with the boundary layer distance. The variations are fairly dramatic around one-tenth of the boundary layer distance. This corresponds to the location of the thin flame front described earlier. The carbon-dioxide mass fraction depicts the most pronounced variation.

Figure 8 shows the effect of the frequency of oscillation on the phase angle variation with distance. At a higher frequency the phase angle increases more rapidly with distance.

Figure 9 is a follow up to Figure 8. It shows that at significantly higher unsteady pressures the rate of phase angle variation with distance remains relatively unchanged.

ADMITTANCE

The admittance, Y, of the carbon is defined as follows :

$$\tilde{Y}=\frac{u_{y\ell}/\bar{a}}{P_\ell/\gamma\bar{P}}$$

Since the acoustic pressure is not necessarily always in phase with the velocity at the surface of the carbon, the admittance may be complex. If the admittance is complex, the reflected wave at the surface may either lead or lag the incident wave by angles ranging from 0 to 180 degrees.

The results of this investigation show that the velocity and acoustic pressure are in phase with each other. Consequently, the admittance is a real number. The results further reveal that the admittance is positive. This implies that the combustion process interacts positively with the sound wave; that is, the combustion process results in an amplification of the sound wave.

5.0 <u>CONCLUSION & RECOMMENDATION</u>

The results obtained indicate that the acoustic oscillations interact positively with the combustion process. Consequently, the combustion process is enhanced when the carbon is subjected to the acoustic oscillations. It should be noted that the analysis performed is linear and the results indicate a trend. Linear oscillations do not have a mechanism for changing mean flow behavior. Non-linear effects are necessarily required for mean flow modification by the acoustics. Since the linear analysis indicates positive interaction, it is recommended that further research be conducted on non-linear effects.

APPENDICES

APPENDIX A : Transformation Technique

This section provides the Caram technique used to obtain the steady-state equations.

CARAM'S TECHNIQUE

The steady system of equations (2-5) to (2-7) are transformed into one differential equation and a set of algebraic equations. In this new form, convergence of the solution is more easily obtained. The following method, as used by Caram (1977), has been used in order to obtain the desired transformation.

Equations of mass and energy reduce to :

$$CO_2 : \quad \frac{d}{dy}\left(\rho D \frac{dY_1}{dy}\right) = -M_1 RR \qquad (A-1)$$

$$CO : \quad \frac{d}{dy}\left(\rho D \frac{dY_2}{dy}\right) = M_2 RR \qquad (A-2)$$

$$O_2 : \quad \frac{d}{dy}\left(\rho D \frac{dY_3}{dy}\right) = M_3 RR/2 \qquad (A-3)$$

$$\frac{d}{dy}\left(\lambda \frac{dT}{dy}\right) = -\Delta H_3 RR \qquad (A-4)$$

The boundary conditions are as follows :

$$CO_2 : \quad -\frac{\rho D}{M_1}\left(\frac{dY_1}{dy}\right)_{y=0} = -R_2 \qquad (A-5)$$

$$CO : \quad -\frac{\rho D}{M_2}\left(\frac{dY_2}{dy}\right)_{y=0} = 2(R_1+R_2) \qquad (A-6)$$

$$O_2 : \quad -\frac{\rho D}{M_3}\left(\frac{dY_3}{dy}\right)_{y=0} = -R_1 \qquad (A-7)$$

$$-\lambda\left(\frac{dT}{dy}\right)_{y=0} = (-\Delta H_1)R_1 + (-\Delta H_2)R_2 \qquad (A-8)$$

At y=1, the boundary conditions are assumed as follows :

$$CO_2 : \quad Y_1 = Y_{1b} \qquad (A-9)$$

$$CO : \quad Y_2 = Y_{2b} \qquad (A-10)$$

$$O_2 : \quad Y_3 = Y_{3b} \qquad (A-11).$$

$$T = T_b \qquad (A-12)$$

Combining A-1 to A-4, the following expressions are obtained :

$$\frac{d}{dy}\left(\rho \frac{D}{M_1} \frac{dY_1}{dy} + \rho \frac{D}{M_2} \cdot \frac{dY_2}{dy}\right) = 0 \qquad (A-13)$$

$$\frac{d}{dy}\left(\rho \frac{D}{M_1} \frac{dY_1}{dy} + 2\rho \frac{D}{M_3} \cdot \frac{dY_3}{dy}\right) = 0 \qquad (A-14)$$

$$\frac{d}{dy}\left(\rho \frac{D}{M_1} \frac{dY_1}{dy} - \frac{\lambda}{\Delta H_3} \cdot \frac{dT}{dy}\right) = 0 \qquad (A-15)$$

If the above equations are integrated, we obtain :

$$\frac{\rho D}{M_1}\frac{dY_1}{dy} + \frac{\rho D}{M_2}\frac{dY_2}{dy} = A' \qquad \text{(A-16)}$$

$$\frac{\rho D}{M_1}\frac{dY_1}{dy} + \frac{2\rho D}{M_3}\frac{dY_3}{dy} = A'' \qquad \text{(A-17)}.$$

$$\frac{\rho D}{M_1}\frac{dY_1}{dy} - \frac{\lambda}{\Delta H_3}\frac{dT}{dy} = A''' \qquad \text{(A-18)}$$

where A', A'', A''' are constants to be determined.

Assuming the Lewis number to be 1, we can write :

$$\rho D = \frac{\lambda}{C_p}$$

and integrating from the surface outward we obtain :

$$\frac{\rho D}{M_1}(Y_1 - Y_{1s}) + \frac{\rho D}{M_2}(Y_2 - Y_{2s}) = A'y \qquad \text{(A-19)}$$

$$\frac{\rho D}{M_1}(Y_1 - Y_{1s}) + \frac{2\rho D}{M_3}(Y_3 - Y_{3s}) = A'' y \tag{A-20}$$

$$\frac{\rho D}{M_1}(Y_1 - Y_{1s}) - \frac{\lambda}{\Delta H_3}(T - T_s) = A''' y \tag{A-21}$$

The constants A', A'', A''' can be found using the above boundary conditions A-5 to A-8

$$A' = -(2R_1 + R_2) \tag{A-22}$$

$$A'' = 2R_1 + R_2 \tag{A-23}$$

$$A''' = \frac{(-\Delta H_1)}{\Delta H_3} R_1 + \left(1 - \frac{\Delta H_2}{\Delta H_3}\right) R_2 \tag{A-24}$$

Using the proposed kinetic equations, the following expression are obtained :

$$A = -A' = A'' = 2K_1 C_{O_{2s}} + k_3 C_{CO_{2s}}$$

$$= \frac{2K_1 \rho Y_{3s}}{M_3} + \frac{k_3 \rho Y_{1s}}{M_1}$$

Substituting back into A-19 to A-21 :

$$(Y_1 - Y_{1s}) + \alpha_1 (Y_2 - Y_{2s}) = -s\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right] \qquad \text{(A-25)}$$

$$(Y_1 - Y_{1s}) + 2\alpha_2 (Y_3 - Y_{3s}) = s\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right] \qquad \text{(A-26)}$$

$$(Y_1 - Y_{1s}) + \alpha_3 (\tau - \tau_s) = s\gamma\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right] \qquad \text{(A-27)}$$

A-25 to A-27 gives three equations for four unknowns. If τ_s is chosen then :

$$Y_{1s} = \frac{Y_{1b} + 2\alpha_2 Y_{3b} - \left[Y_{1b} + \alpha_3(1-\tau_s)\right](\alpha_2+\beta_1)/\gamma\beta_1}{1+\beta_2 - (1+\gamma\beta_2)(\beta_1+\alpha_2)/\gamma\beta_1} \qquad \text{(A-28)}$$

$$Y_{3s} = \left[Y_{1b} - Y_{1s} + \alpha_3(1-\tau_s) - \gamma\beta_2 Y_{1s}\right]/2\gamma\beta_1 \qquad \text{(A-29)}$$

$$Y_{2s} = \left[Y_{1b} - Y_{1s} + \alpha_1 Y_{2b} + 2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]/\alpha_1 \qquad \text{(A-30)}$$

Therefore, if surface temperature is known, the mass fractions can be determined.

If carbon-dioxide is chosen as a key component, A-1 can be rewritten as follows :

$$\frac{d^2 Y_1}{ds^2} = -\beta_3 \exp(-\delta/\tau)\, Y_2\, Y_3^{1/2} \quad \text{(A-31)}$$

$\Rightarrow$

$$Y_2 = \left[Y_{1s} - Y_1 + \alpha_1 Y_{2s} - s\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]\right] / \alpha_1 \quad \text{(A-32)}$$

$$Y_3 = \left[Y_{1s} - Y_1 + 2\alpha_2 Y_{3s} + s\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]\right] / 2\alpha_2 \quad \text{(A-33)}$$

$$\tau = \left[Y_{1s} - Y_1 + \alpha_3 \tau_s + s\,\gamma\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]\right] / \alpha_3 \quad \text{(A-34)}$$

A-31 can be solved using the boundary conditions A-5 and A-9. Therefore, once the ambient conditions are fixed and the surface temperature guessed, the surface concentrations can be determined. Consequently, the integration is performed. If the proper guess of the temperature was made then $Y_1(1) = Y_{1b}$.

If not, a new value of τ_s must be tried using a systematic iteration procedure.

<u>**NOTE:**</u>

$$\alpha_1 = \frac{M_1 D}{M_2 D} \qquad \alpha_2 = \frac{M_1 D}{M_3 D}$$

$$\alpha_3 = -\frac{2\lambda M_1 T_b}{\Delta H_3 \rho D} \qquad \beta_1 = \frac{k_1 M_1 l}{D M_3} .$$

$$\beta_2 = \frac{K_3 l}{D} \qquad \beta_3 = \frac{K_2 l^2 M_1 \rho^{1/2}}{D M_2 M_3^{1/2}}$$

$$\delta = \frac{E_2}{RT_b} \qquad \gamma = \frac{-\Delta H_1}{\Delta H_3}$$

$$\zeta = y/l \qquad \tau = T/T_b$$

APPENDIX B : Computer Program Equations

This section contains the equations used in the computer program.

EQUATIONS INCORPORATED INTO COMPUTER PROGRAM
****

STEADY CASE :

$$R_1 = K_1 \exp(-E_1/RT_s) C_{3s}$$

$$K_1 = 3.007 \times 10^5 \ m/s$$

$$R_2 = K_2 \exp(-E_2/RT_s) C_{1s}$$

$$K_2 = 4.016 \times 10^8 \ m/s$$

$$RR = K_3 \exp(-E_3/RT) C_2 C_3^{1/2}$$

$$K_3 = 8.107 \times 10^8 \ m^{3/2}/kg\cdot mol^{1/2}\cdot s$$

$$\frac{d^2 Y_1}{ds^2} = -\beta_3 \exp(-\delta/\tau) Y_2 Y_3^{1/2}$$

$$Y_2 = \left[Y_{1s} - Y_1 + \alpha_1 Y_{2s} - s\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]\right]/\alpha_1$$

$$Y_3 = \left[Y_{1s} - Y_1 + 2\alpha_2 Y_{3s} + s\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]\right]/2\alpha_2$$

$$\tau = \left[Y_{1s} - Y_1 + \alpha_3 \tau_s + s\gamma\left[2\beta_1 Y_{3s} + \beta_2 Y_{1s}\right]\right]/\alpha_3$$

OSCILLATORY CASE :

$$u_{yf} = \frac{R\bar{T}}{\bar{p}} \cdot T_{s_f} \left[K_1 \frac{E_1}{R\bar{T}_s^2} e^{-\frac{E_1}{R\bar{T}_s}} \bar{C}_{3_s} + K_2 \frac{E_2}{R\bar{T}_s^2} e^{-\frac{E_2}{R\bar{T}_s}} \cdot \bar{C}_{1s1s1ss} \right.$$

$$Y_{CO_2 f} = - \frac{u_{yf}}{i\omega} \frac{dY_1}{dy}$$

$$Y_{CO_f} = \frac{u_{yf}}{i\omega\alpha_1} \frac{dY_1}{dy}$$

$$Y_{O_2 f} = \frac{u_{yf}}{2i\omega\alpha_2} \frac{dY_1}{dy}$$

$$\lambda \frac{d^2 T_f}{dy^2} - \left[\sum^1 (RR_i)_f \Delta h \right] = C_p \left[i\omega\bar{\rho} T_f + \bar{\rho} u_{yf} \frac{d\bar{T}}{dy} \right]$$

$$- i\omega \left[\bar{\rho} R T_f + \rho_f R\bar{T} \right]$$

$$\tilde{Y} = \frac{u_{yf}/\bar{a}}{P_f/\gamma\bar{P}}$$

APPENDIX C : Order of Magnitude Analysis

This section contains the Order of Magnitude Analysis.

ORDER OF MAGNITUDE

This section shows the detailed order of magnitude analysis performed on equations (2-13) to (2-16). This analysis was performed in an effort to simplify the governing unsteady equations.

MOMENTUM

$$\bar{\rho} D \frac{d^2 u_{yf}}{dy^2} = i\omega \bar{\rho}\, u_{yf} + \frac{d}{dy} P_f$$

$$P_f^* = \frac{P_f}{P_R} \quad ; \quad y^* = \frac{y}{a/\omega} \quad \rightarrow \quad a = \left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}$$

$$u_{yf}^* = \frac{u_{yf}}{\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}$$

$$\bar{\rho} D \frac{d^2 u_{yf}^*}{dy^{*2}} \cdot \frac{\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2} \omega^2}{\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}} = i\omega \bar{\rho}\, u_{yf}^* \left(\frac{\gamma P_R}{\rho_R}\right)^{1/2} + \frac{dP_f^*\, P_R}{dy^* \left(\frac{\gamma P_R}{\rho_R}\right)^{1/2} / \omega}$$

Multiplying through by $\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2} / \bar{\rho} D \omega^2$

$$\frac{d^2 u_{yf}^*}{dy^{*2}} = \frac{i\omega \bar{\rho} \left(\frac{\gamma P_R}{\rho_R}\right)}{\bar{\rho} D \omega^2} u_{yf}^* + \frac{P_R\, \omega}{\bar{\rho} D \omega^2} \frac{d}{dy^*} P_f^*$$

$$\frac{\omega\bar{\rho}\left(\frac{\gamma P_R}{\rho_R}\right)}{\bar{\rho}\, D\, \omega^2} = \frac{\gamma P_R}{\rho_R D \omega} = \frac{1.3 \times 101 \times 10^3}{1.22 \times 2 \times 10^{-4} \times 100 \times 2\pi}$$

$$= 8.5 \times 10^5$$

$$\frac{P_R\, \omega}{\bar{\rho}\, D\, \omega^2} = \frac{101 \times 10^3}{1.22 \times 2 \times 10^{-4} \times 100 \times 2\pi} = 6.52 \times 10^5$$

Therefore, the momentum equation becomes :

$$0 = i\omega\bar{\rho}\, u_{yf} + \frac{d}{dy} P_f$$

(SPECIES)

$$D\bar{\rho}\ \frac{d^2Y_f}{dy^2} = i\omega\bar{\rho}Y_f + \bar{\rho}u_{yf}\frac{d\bar{Y}}{dy} - \frac{d^2}{dy^2}(D\rho_f\bar{Y})$$

$$D\bar{\rho}\ \frac{d^2Y_f\ \omega^2}{dy^{*2}\left(\frac{\gamma P_R}{\rho_R}\right)} = i\omega\bar{\rho}Y_f + \bar{\rho}u^*_{yf}\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}\cdot\frac{d\bar{Y}\cdot\omega}{dy^*\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}$$

$$-\frac{d^2\omega^2}{dy^{*2}\left(\frac{\gamma P_R}{\rho_R}\right)}\cdot D\rho_f^*\rho_R\bar{Y}$$

Multiplying through by $\dfrac{\gamma P_R}{\rho_R\bar{\rho}D\omega^2}$,

$$\frac{d^2Y_f}{dy^{*2}} = \frac{i\gamma P_R\omega\bar{\rho}Y_f}{\rho_R\bar{\rho}D\omega^2} + \frac{\gamma P_R\bar{\rho}u^*_{yf}\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}\omega}{\rho_R\bar{\rho}D_{O_2}\omega^2\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}$$

$$-\frac{\omega^2D\rho_R\gamma P_R}{\rho_R\bar{\rho}D\omega^2\left(\frac{\gamma P_R}{\rho_R}\right)}\frac{d^2}{dy^{*2}}\rho_f^*\bar{Y}$$

$$\frac{\gamma P_R\omega\bar{\rho}}{\rho_R\bar{\rho}D\omega^2} = \frac{1.3\times101\times10^3}{1.22\times2\times10^{-4}\times2\pi\times100} = 8.5\times10^5$$

$$\frac{\gamma P_R \bar{\rho} \omega}{\rho_R \bar{\rho} D \omega^2} = \frac{1.3 \times 101 \times 10^3}{1.22 \times 2 \times 10^{-4} \times 2\pi \times 100} = 8.5 \times 10^5$$

$$\frac{\gamma P_R \rho_R}{\bar{\rho} \gamma P_R} = \frac{1.22}{0.35} = 3.5$$

Therefore, the species equation becomes :

$$0 = i\omega \bar{\rho} Y_f + \bar{\rho} u_{yf} \frac{d\bar{Y}}{dy}$$

(CONTINUITY)

$$\frac{du_{yf}}{dy} = -\frac{i\omega\rho_f}{\bar{\rho}} - \frac{u_{yf}}{\bar{\rho}}\frac{d\bar{\rho}}{dy}$$

$$\frac{du_{yf}^{*}\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}\omega}{dy^{*}\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}} = \frac{-i\omega\rho_f^{*}\rho_R}{\bar{\rho}}$$

$$-\frac{u_{yf}^{*}\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}{\bar{\rho}}\frac{d\bar{\rho}\,\omega}{dy^{*}\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}$$

Dividing by ω ,

$$\frac{du_{yf}^{*}}{dy^{*}} = -i\,\frac{\rho_f^{*}\rho_R}{\bar{\rho}} - \frac{u_{yf}^{*}}{\bar{\rho}}\cdot\frac{d\bar{\rho}}{dy^{*}}$$

$$\frac{\rho_R}{\bar{\rho}} = \frac{1.22}{.35} = 3.5$$

Therefore, the continuity equation becomes :

$$\frac{du_{yf}}{dy} = -\frac{u_{yf}}{\bar{\rho}}\cdot\frac{d\bar{\rho}}{dy}$$

(ENERGY)

$$\lambda \frac{d^2 T_f}{dy^2} - \left[\sum (RR_i)_f \Delta h\right] = C_p\left[i\omega \bar{\rho} T_f + \bar{\rho} u_{yf} \frac{d\bar{T}}{dy}\right]$$

$$- i\omega\left[\bar{\rho} R T_f + \rho_f R \bar{T}\right]$$

$$\frac{\lambda d^2 T^* T_R \omega^2}{dy^{*2}\left(\frac{\gamma P_R}{\rho_R}\right)} - \sum (\Delta h)(RR_i)_f = C_p i\omega \bar{\rho} \dot{T}^* T_R$$

$$+ C_p \bar{\rho} u^*_{yf} \left(\frac{\gamma P_R}{\rho_R}\right)^{1/2} \cdot \frac{d\bar{T}, \omega}{dy^*\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}} - i\omega \bar{\rho} R T^* T_R$$

$$- i\omega R \bar{T} \rho^* \rho_R - \bar{\rho} \bar{T} \frac{d}{dy^*} \frac{\omega}{\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}} \cdot C_p \cdot D \cdot \sum \frac{dY_f}{dy^*} \frac{\omega}{\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}$$

$$-(\bar{\rho} T^* T_R + \rho^* \rho_R \bar{T}) \frac{d\ \omega}{dy^*\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}} \cdot C_p \cdot D \cdot \sum \frac{d\bar{Y}}{dy^*} \cdot \frac{\omega}{\left(\frac{\gamma P_R}{\rho_R}\right)^{1/2}}$$

Multiplying through by $\frac{\gamma P_R}{\rho_R \lambda T_R \omega^2}$,

$$\frac{d^2T^*}{dy^{*2}} - \frac{\gamma P_R}{\rho_R \lambda T_R \omega^2} \sum (\Delta h) RR_i = \frac{i c_p \omega \bar{\rho} T_R \gamma P_R}{\rho_R \lambda T_R \omega^2} T^*$$

$$+ \frac{\gamma P_R c_p \bar{\rho} \omega}{\rho_R \lambda T_R \omega^2} \cdot u_{yf}^* \frac{d\bar{T}}{dy^*} - \frac{i \omega \bar{\rho} R T_R \gamma P_R}{\rho_R \lambda T_R \omega^2} \cdot T^*$$

$$- \frac{i \omega R \bar{T} \rho_R \gamma P_R}{\rho_R \lambda T_R \omega^2} \rho^* - \frac{\bar{\rho} \bar{T} \omega^2 \gamma P_R \rho_R c_p D}{\rho_R \lambda T_R \omega^2 (\gamma P_R)} \cdot \frac{d}{dy^*} \sum \frac{dY_i}{dy^*}$$

$$- \frac{\bar{\rho} T_R c_p D \omega^2 \rho_R \gamma P_R}{\rho_R \lambda T_R \omega^2 \gamma P_R} T^* \frac{d}{dy^*} \sum \frac{d\bar{Y}}{dy^*}$$

$$- \frac{\rho_R \bar{T} c_p D \omega^2 \rho_R \gamma P_R}{\rho_R \lambda T_R \omega^2 \gamma P_R} \rho^* \frac{d}{dy^*} \sum \frac{d\bar{Y}}{dy^*}$$

$$\frac{\gamma P_R}{\rho_R \lambda T_R \omega^2} \sum' (\Delta h) RR_{i_f} = \text{large value}$$

$$\frac{C_p \omega \bar{\rho} T_R \gamma P_R}{\rho_R \lambda T_R \omega^2} = \frac{\gamma P_R}{\rho_R D \omega} = \frac{1.3 \times 101 \times 10^3}{1.22 \times 2 \times 10^{-4} \times 100 \times 2\pi} = 8.5 \times 10$$

$$\frac{\gamma P_R C_p \bar{\rho} \omega}{\rho_R \lambda \omega^2} = \frac{\gamma P_R}{\rho_R D \omega} = 8.5 \times 10^5$$

$$\frac{\omega \bar{\rho} R T_R \gamma P_R}{\rho_R \rho D C_p T_R \omega^2} = \frac{\gamma R P_R}{\rho_R D C_p \omega} = \frac{1.3 \times 287 \times 101 \times 10^3}{1.22 \times 2 \times 10^{-4} \times 1004 \times 100 \times 2\pi}$$

$$= 2.5 \times 10^5$$

$$\frac{\omega R \bar{T} \rho_R \gamma P_R}{\rho_R \rho D C_p T_R \omega^2} = \frac{\gamma R P_R}{\rho_R D C_p \omega} = 2.5 \times 10^5$$

$$\frac{\bar{\rho}\,\bar{T}\,\omega^2 \gamma P_R \rho_R C_p D}{\rho_R \rho C_p D T_R \omega^2 \gamma P_R} = 1$$

$$\frac{\bar{\rho}\,T_R C_p D\,\omega^2 \rho_R \gamma P_R}{\rho_R \rho C_p D T_R \omega^2 \gamma P_R} = 1$$

$$\frac{\rho_R \bar{T} C_p D\,\omega^2 \rho_R \gamma P_R}{\rho_R \rho C_p D T_R \omega^2 \gamma P_R} = 1$$

And therefore the energy equation is still :

$$\lambda \frac{d^2 T_f}{dy^2} - \left[\sum_i (RR_i)_f \Delta h\right]$$

$$= C_p\left[i\omega\bar{\rho}\,T_f + \bar{\rho}\,u_{yf}\frac{d\bar{T}}{dy}\right] - i\omega\left[\bar{\rho} R T_f + \rho_f R \bar{T}\right]$$

APPENDIX D : Figures

The following pages contain Figures 2 to 9.

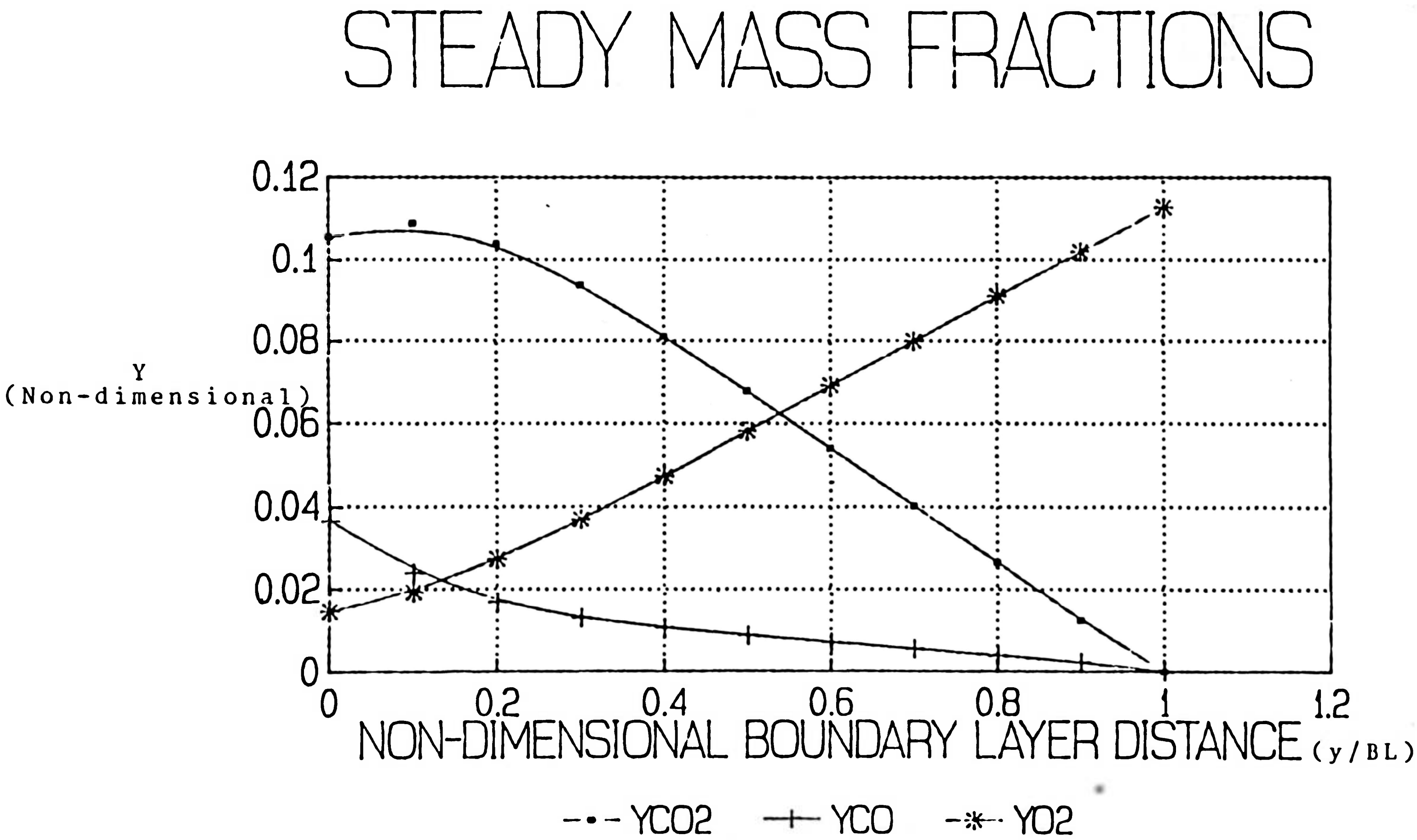

Figure 2.0 : Steady mass fractions.

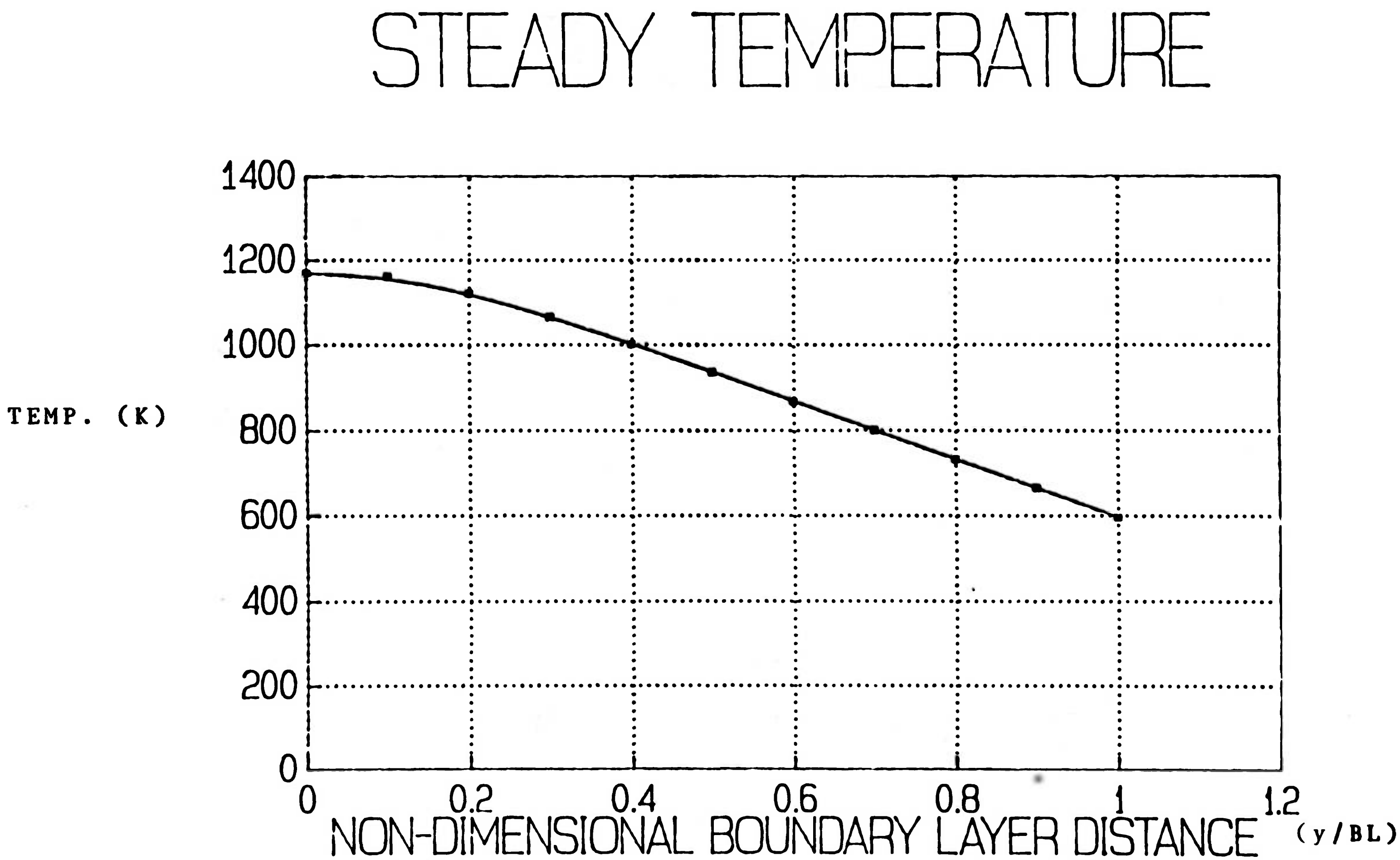

Figure 3.0 : Steady temperature

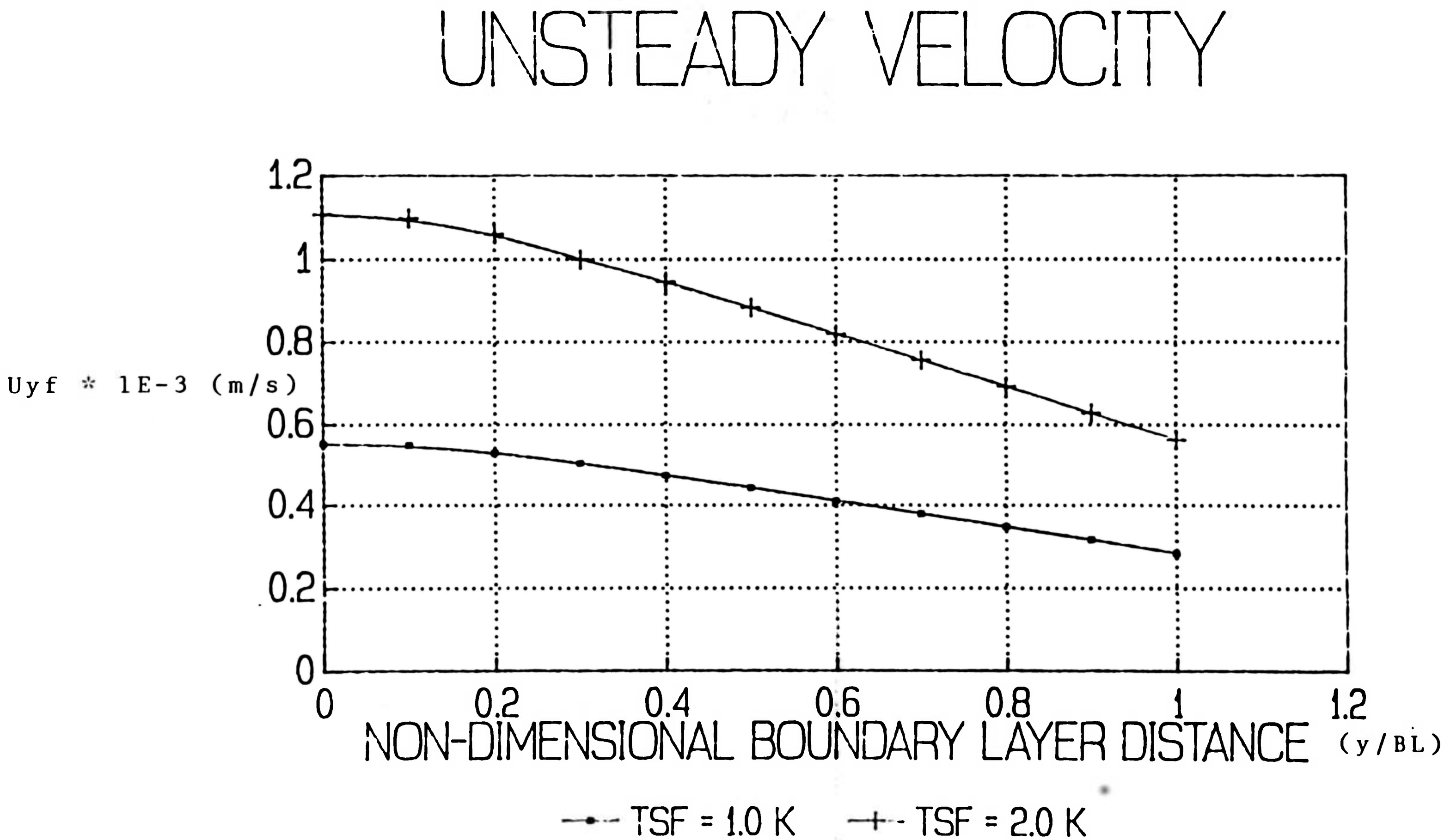

Figure 4.0 : Unsteady velocity

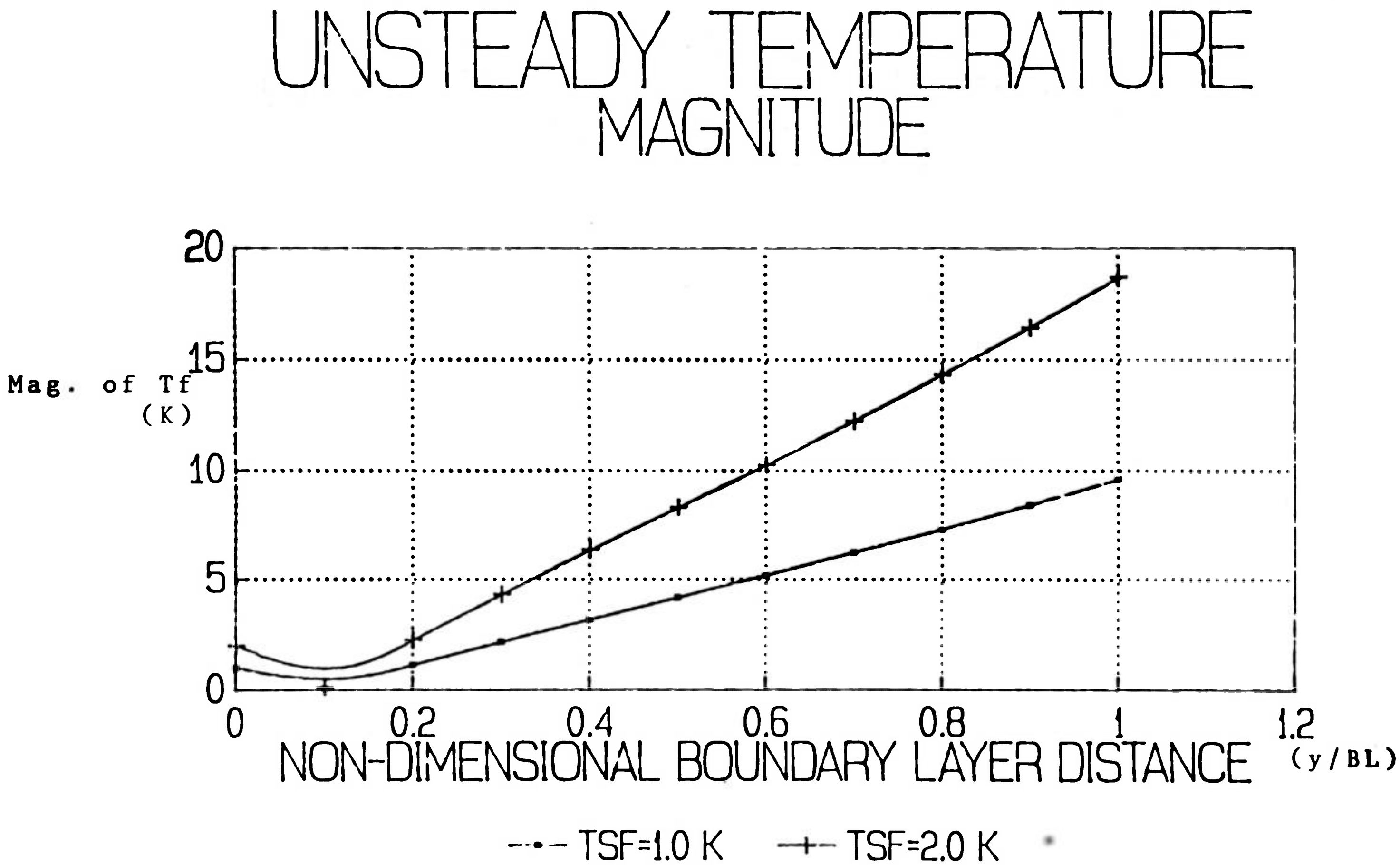

Figure 5.0 : Unsteady Temperature(**magnitude**)

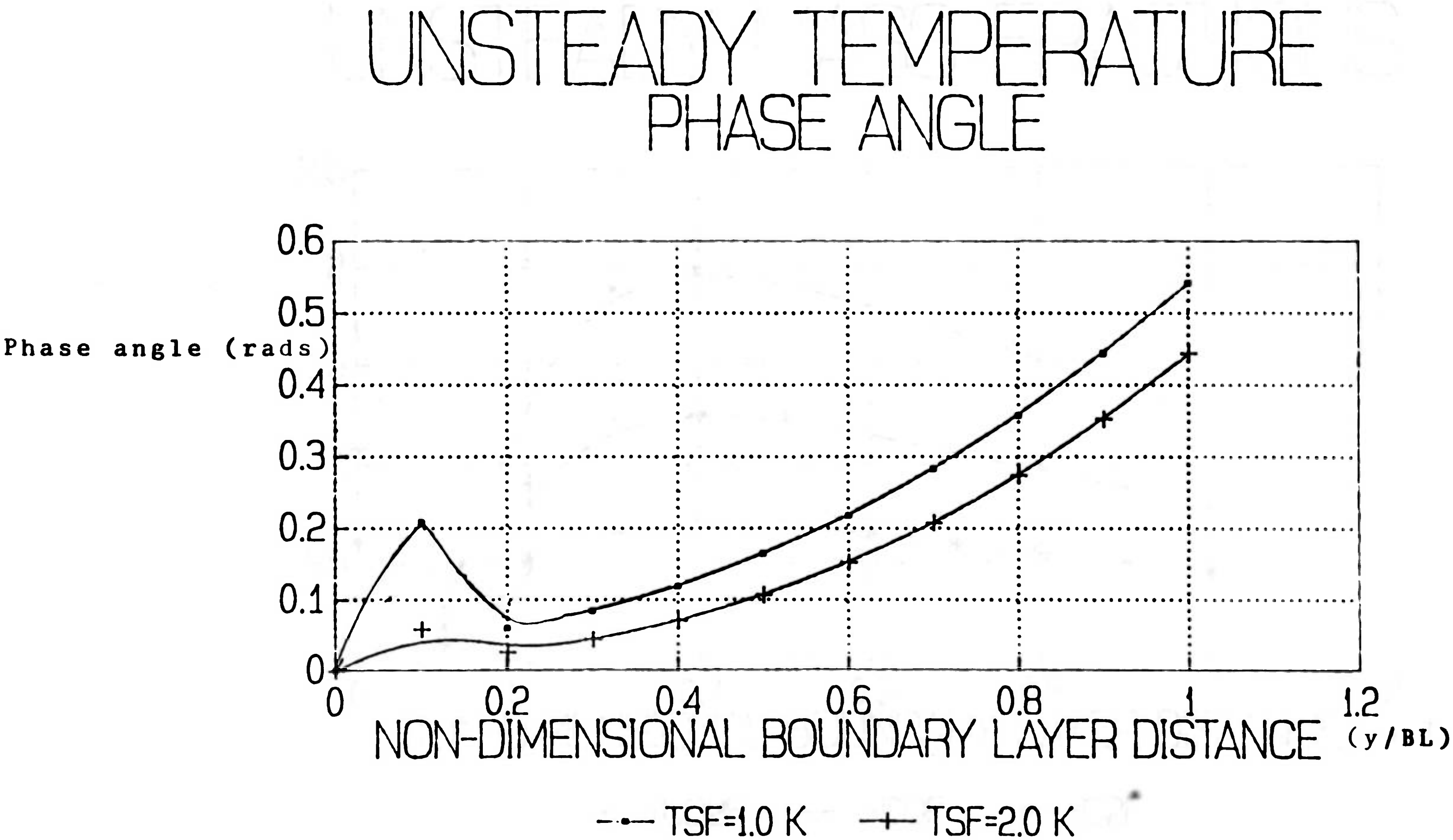

Figure 6.0 : Unsteady temperature (phase)

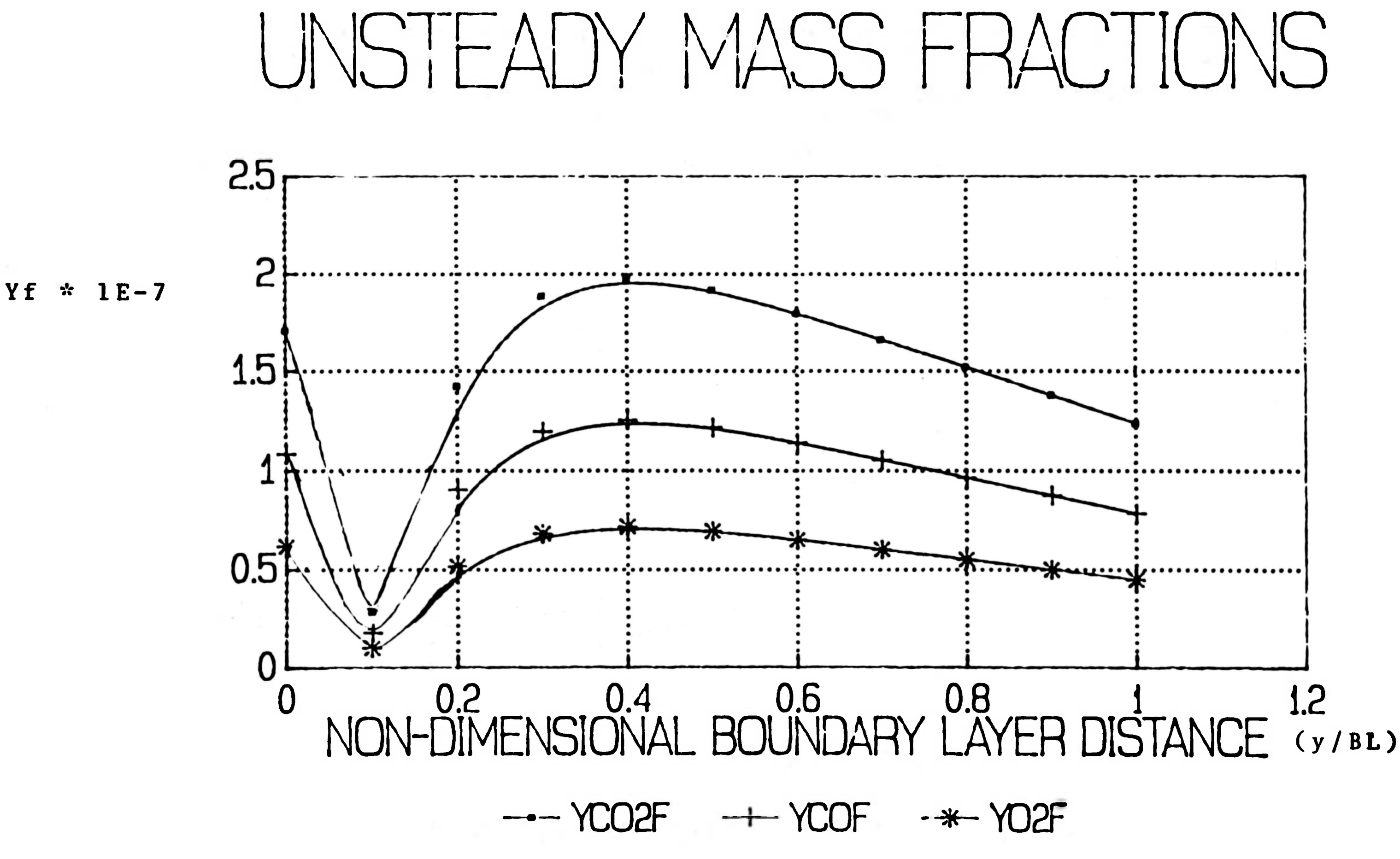

Figure 7.0 : Unsteady mass fractions

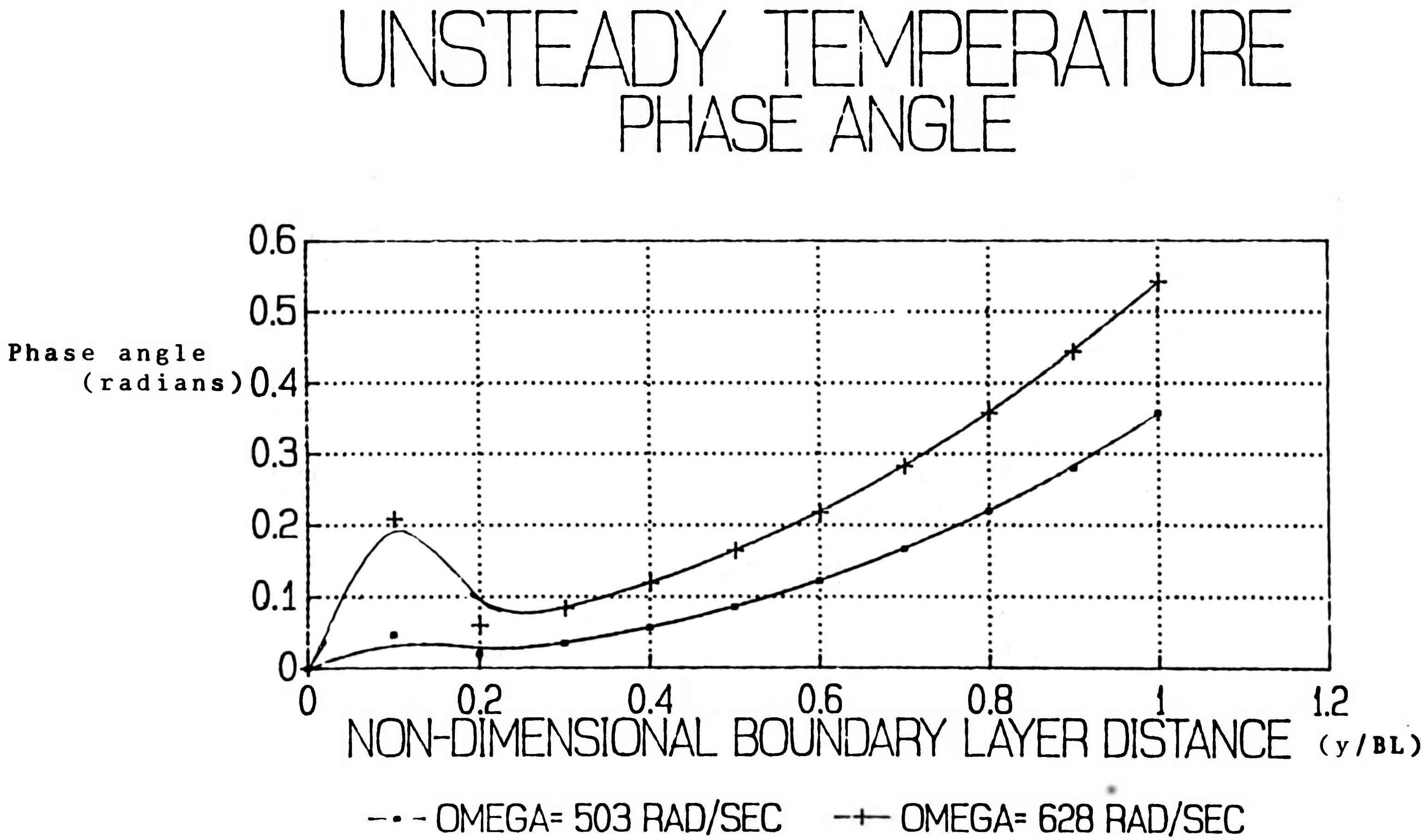

Figure 8.0 : Unsteady temperature(phase angle), frequency variation.

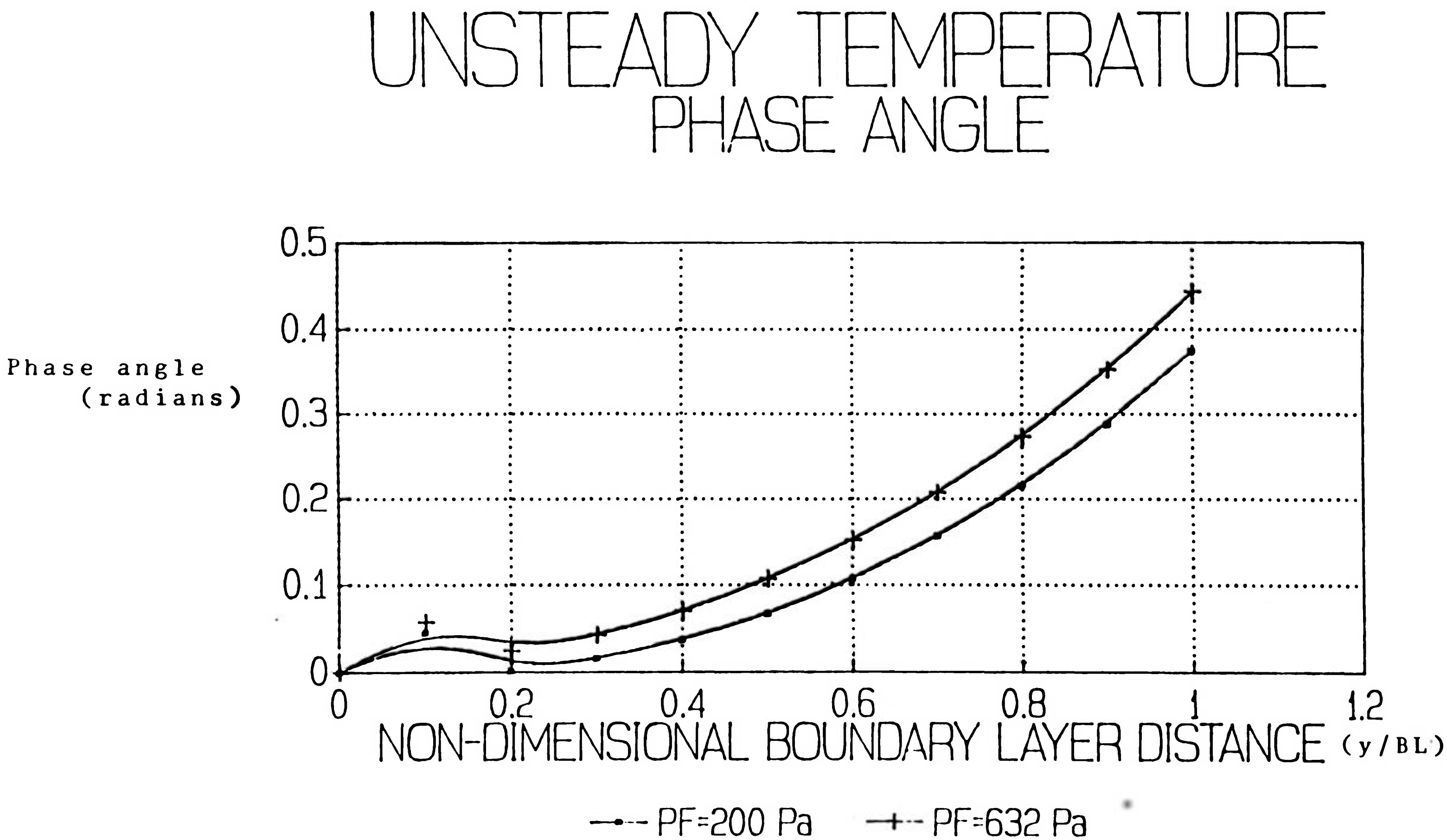

Figure 9.0 : Unsteady temperature(phase angle), pressure variation.

APPENDIX E : Computer Program & Output

The following pages consist of a listing of the computer program and the various outputs.

```
*******************************************************************************
ERAURSCS    VIVE        4/10/91    13:26:58  E.S.T.   WAS THE ORIGIN
DEST: IBM4234   FILE: 2111  NAME: VIVEK       FORTRAN       DIST: USER01
*******************************************************************************
```

```
FILE: VIVEK    FORTRAN  A1  ERAU VM/CMS REL 5.1

***************************************************************************
*                                                                         *
*     PROGRAM TO INVESTIGATE THE EFFECT OF ACOUSTIC                       *
*     OSCILLATIONS ON THE BURNING OF CARBON.                              *
*                                                                         *
***************************************************************************
*                                                                         *
*     AUTHOR    VIVEK LALL                                                *
*               EMBRY-RIDDLE AERONAUTICAL UNIVERSITY                      *
*               DAYTONA BEACH, FLORIDA                                    *
*               APRIL, 1991.                                              *
*                                                                         *
***************************************************************************

      PROGRAM MAIN
      EXTERNAL FCN
      REAL K1,K2
      COMPLEX L,TF,TSF,UYF,YCO2F,YCOF,YO2F,TERM1,TERM2,TERM3,
     1 TERM4,TERM6,TERM7,TERM8,YCO2,YCO,YO2,R1,R2,CST,TFR TFI,MAGTF
     2 ,PHITF,FSF,FFR,FFI,FF,ADMIT,UYFS,YCO2S,YCOS,YO2S
      DIMENSION XI(8),XX(8),DY1DY(11),STORE(8,11),TSS(11)
     1 ,F1(11),F2(11),F3(11),C2(11),C3(11)
      COMMON BL,Y1S,Y2S,Y3S,TAUS,ALPHA1,ALPHA2,ALPHA3,BETA1,BETA2,GAMMA
     1   ,DELTA,BETA3,Y2,Y3,TAU,TF,TSF,TERM1,TERM2,TERM3,TERM4,
     2    TERM6,TERM7,TAMB,TERM8,K1,K2,C2S,C3S,TSURF R1,R2,YCO2,YCO,YO2
     3    ,UYF,C1S,ADMIT,OMEGA,FF,FSF,UYFS,YCO2S,YCOS,YO2S
      PRINT*,'TSURF = '
      READ*,TSURF
      PRINT*,' TAMB = '
      READ*,TAMB
      PRINT*,'Y1B = '
      READ*,Y1B
      PRINT*,'Y2B = '
      READ*,Y2B
      PRINT*,'Y3B = '
      READ*,Y3B
      PRINT*,'BOUNDARY LAYER THICKNESS = '
      READ*,BL
C     PRINT*,'INPUT FREQUENCY OF OSCILLATION'
C     READ*,OMEGA
      PRINT*,'INPUT TSF'
      READ*,TSF
      TAUS=TSURF/TAMB
      K1=3.007E5*EXP(-17966./ TSURF)
      K2=4.1E9*EXP(-29790./ TSURF)
      ALPHA1=44./28.
      ALPHA2=44./32.
      ALPHA3=-(2.*6.7E-2*44.*TAMB)/((2.82E8)*0.35*2.E-4)
      BETA1=(K1*44.*BL)/(2.E-4*32.)
      BETA2=(K2*BL)/(2.E-4)
      BETA3=(1.3E11*(.002)**0.5*(BL)**2*(0.35)**0.5*44.)/(2E-4*28.
     1   *32.**0.5)
      DELTA=(30000./(1.9872*TAMB))
      GAMMA=(1.12E8/2.82E8)
      DENOM=1+BETA2-(1+GAMMA*BETA2)*(BETA1+ALPHA2)/(GAMMA*BETA1)
```

FILE. VIVEK   FORTRAN A1 ERAU VM/CMS REL 5.1

```
      Y1S=(Y1B+(2.*ALPHA2*Y3B)-(Y1B+ALPHA3*(1.-TAUS))*(ALPHA2+BETA1)/
     1     (GAMMA*BETA1))/DENOM
      Y3S=((Y1B-Y1S)+ALPHA3*(1.-TAUS)-(GAMMA*BETA2*Y1S))/(2.*GAMMA
     1     *BETA1)
      Y2S=((Y1B-Y1S)+ALPHA1*Y2B+2.*BETA1*Y3S+BETA2*Y1S)/ALPHA1
C     PRINT*,Y1S,Y2S,Y3S
      C3S=((Y3S/32.)/(Y1S/44.+Y2S/28.+Y3S/32.))*101.E3/(8314.4*TSURF)
      C1S=((Y1S/44.)/(Y1S/44.+Y2S/28.+Y3S/32.))*101.E3/(8314.4*TSURF)
      R1=K1*(17966./(TSURF**2))*C3S*TSF
      R2=K2*(29790./(TSURF**2))*C1S*TSF
      TT=0.
      NV=8
      NR=8
      XI(1)=Y1S
      XI(2)=BETA2*Y1S
      XI(3)=REAL(TSF)
      CST=((-1/(6.7E-2))*1E-3*(-1.12E8*R1+1.7E8*R2))
C     PRINT*,'CST=',CST
      XI(4)=REAL(CST)
      XI(5)=AIMAG(TSF)
      XI(6)=AIMAG(CST)
      PSF=(632.46,0)
      XI(7)= REAL(PSF)
      XI(8)= AIMAG(PSF)
C     PRINT*,'INITIAL VALUES : '
C     PRINT*,XI
      IN=0
      II=1
      ISET=0
      ACCUR=1.E-1
      IPRINT=0
      PRINT*,'ENTER STEP SIZE    :
      READ*,DX
      PRINT*,'THE RESULTS SHOWN BELOW PROVIDE THE VARIOUS DESIRED'
      PRINT*,'VALUES FROM THE SURFACE OF THE CARBON (y=0) TO THE'
      PRINT*,'BOUNDARY (y=1) IN STEPS OF 0.1.(NB : THE PRINTOUT'
      PRINT*,'STARTS WITH y=0.1 AND GOES TO y=1.0 AND CONSEQUENTLY   '
      PRINT*,'THE VALUES AT THE CARBON SURFACE (y=0) ARE PRINTED'
      PRINT*,'                                              '
      PRINT*,'-------------------------------------------------------------
   50 TP=TT+DX
   70 CALL RKINIT(FCN,NV,TT,XI,ACCUR,NR,IPRINT,IN,ISET,STORE,TP,XX,IRR)
      DO 75 J=1,6
      XI(J)=XX(J)
   75 CONTINUE
      DY1DY(II)=XX(2)
      TT=TP
      F1(II)=XX(1)
      F2(II)=Y2
      F3(II)=Y3
      TSS(II)=TAU*TAMB
      YCO2F=YCO2
      YCOF=YCO
      YO2F=YO2
      TFR=XX(3)
```

```
      TFI=XX(5)
      TF=CMPLX(XX(3),XX(5))
      MAGTF=(XX(3)**2+XX(5)**2)**0.5
      PHITF=ATAN(XX(5)/XX(3))
      PFR=XX(7)
      PFI=XX(8)
      PF=CMPLX(XX(7),XX(8))
      IF(IRR)90,100,80
   80 PRINT*,'ERROR RETURN'
      GO TO 200
   90 PRINT*,'BAD ACCURACY SETTING'
  100 PRINT*,'STEADY VALUES :'
      PRINT*,'                                                        '
      PRINT*,'MASS FRACTION OF CO2 =',XX(1)
      PRINT*,'MASS FRACTION OF CO  =',Y2
      PRINT*,'MASS FRACTION OF O2  =',Y3
      PRINT*,'TEMPERATURE          =',(TAU*TAMB)
      PRINT*,'                                                        '
      PRINT*,'UNSTEADY VALUES :'
      PRINT*,'                                                        '
      PRINT*,'MASS FRACTION OF CO2 =',YCO2F
      PRINT*,'MASS FRACTION OF CO  =',YCOF
      PRINT*,'MASS FRACTION OF O2  =',YO2F
      PRINT*,'TEMPERATURE          =',TF
      PRINT*,'MAGNITUDE OF TEMP.   =',MAGTF
      PRINT*,'PHASE ANGLE OF TEMP. =',PHITF
      PRINT*,'VELOCITY IN Y-DIREC. =',UYF
      PRINT*,'                                                        '

      PRINT*,'----------------------------------------------------------'
      II=II+1
      IF (TP-1.0)50,200,200
C*********************************************************************
  200 PRINT*,'*******************VALUES AT CARBON SURFACE***************
     1************'
      PRINT*,'STEADY MASS FRACTION OF CO2 =',Y1S
      PRINT*,'STEADY MASS FRACTION OF CO  =',Y2S
      PRINT*,'STEADY MASS FRACTION OF O2  =',Y3S
      PRINT*,'STEADY TEMPERATURE          =',TSURF
      PRINT*,'----------------------------------------------------------'
      PRINT*,'UNSTEADY MASS FRACTION OF CO2    =',YCO2S
      PRINT*,'UNSTEADY MASS FRACTION OF CO     =',YCOS
      PRINT*,'UNSTEADY MASS FRACTION OF O2     =',YO2S
      PRINT*,'UNSTEADY TEMPERATURE             =',TSF
      PRINT*,'UNSTEADY VELOCITY IN Y-DIRECTION =',UYFS
      PRINT*,'ADMITTANCE                       =',ADMIT
      PRINT*,'**********************************************************
     1************'
      STOP
      END
C*********************************************************************
C*********************************************************************
C*********************************************************************
C*********************************************************************
      SUBROUTINE FCN(T,X,D)
```

```
FILE: VIVEK    FORTRAN  A1  ERAU VM/CMS REL 5.1

      REAL K1,K2,K3
      COMPLEX RHS,PF,L,TF,TSF,UYF,YCO2,YCO,YO2,TERM1,TERM2,TERM3,TERM4,
     1   TERM6,TERM7,TERM8,R1,R2,CST,RHSR,RHSI,ADMIT,RHS2,RHSR2,RHSI2
     2  ,UYFS,PSF,YCO2S,YCOS,YO2S
      DIMENSION X(8),D(8)
      COMMON BL,Y1S,Y2S,Y3S,TAUS,ALPHA1,ALPHA2,ALPHA3,BETA1,BETA2
     1 ,GAMMA,DELTA,BETA3,Y2,Y3,TAU,TF,TSF,TERM1,TERM2,TERM3,TERM4
     2 ,TERM6,TERM7,TAMB,TERM8,K1,K2,C2S,C3S,TSURF,R1,R2,YCO2,YCO,YO2
     3  ,UYF,C1S,ADMIT,OMEGA,PF,PSF,UYFS,YCO2S,YCOS,YO2S
      L=CMPLX(0.,1.)
      Y2=(Y1S-X(1)+ALPHA1*Y2S-T*(2.*BETA1*Y3S+BETA2*Y1S))/ALPHA1
      Y3=(Y1S-X(1)+2.*ALPHA2*Y3S+T*(2.*BETA1*Y3S+BETA2*Y1S))/(2*ALPHA2)
      TAU=(Y1S-X(1)+ALPHA3*TAUS+T*GAMMA*(2.*BETA1*Y3S+BETA2*Y1S))/ALPHA3
      D(1)=X(2)
      D(2)=-BETA3*EXP(-DELTA/TAU)*Y2*Y3**0.5
C***********************************************************************
C*******************UNSTEADY EQUATIONS**********************************
C***********************************************************************

      OMEGA=628.32
      PF=CMPLX(X(7),X(8))
C     PRINT*,'TSURF',TSURF
C     PRINT*,'TSF',TSF
C     PRINT*,'C3S',C3S
C     PRINT*,'C1S',C1S
C     PRINT*,'K1',K1
C     PRINT*,'K2',K2
      K3=(9.107E8)*EXP(-15098/(TAU*TAMB))
C     PRINT*,'K3=',K3
      TERM6=K1*(17966./(TSURF**2))*C3S
C     PRINT*,'TERM6=',TERM6
      TERM7=K2*(29790./(TSURF**2))*C1S
C     PRINT*,'TERM7=',TERM7
      UYF=TSF*(TERM6+TERM7)*8314.4*TAU*TAMB/101.E3
      UYFS=TSF*(TERM6+TERM7)*8314.4*TSURF/101.E3
      ADMIT=(1.3/(1.3**.5))*101.E3*UYFS*(1/(287*TSURF)**.5)*(1/PSF)
C     PRINT*,'UYF',UYF
      C2=((Y2/28.)/(X(1)/44.+Y2/28.+Y3/32.))*101.E3
     1 /(8314.4*TSURF)
      C3=((Y3/32.)/(X(1)/44.+Y2/28.+Y3/32.))*101.E3
     1 /(8314.4*TSURF)
C     PRINT*,'C2=',C2,'C3=',C3
      TERM8=K3*(15098/((TAU*TAMB)**2))*C2*C3**0.5
C     PRINT*,'TERM8=',TERM8
      TERM1=-2.82E8*TERM8
C     PRINT*,'TERM1=',TERM1
      TERM2=((1004.*L*OMEGA*29.*101.E3)/(8314.4*TAU*TAMB))
C     PRINT*,'TERM2=',TERM2
      TERM3=((1004.*UYF*101.E3)/(8314.4*TAU*TAMB))*(-TAMB*X(2)/ALPHA3)
C     PRINT*,'TERM3=',TERM3
      TERM4=(L*OMEGA*PF)
C     PRINT*,'TERM4=',TERM4
      YCO2=-(UYF/(L*OMEGA))*X(2)
      YCO2S=-(UYFS/(L*OMEGA))*BETA2*Y1S
C     PRINT*,'YCO2=',YCO2
```

FILE: VIVEK FORTRAN A1 ERAU VM/CMS REL 5.1

```
      YCO=(UYF/(L*OMEGA*ALPHA1))*X(2)
      YCOS=(UYFS/(L*OMEGA*ALPHA1))*BETA2*Y1S
C     PRINT*,'YCO=',YCO
      YO2=(UYF/(2*L*OMEGA*ALPHA2))*X(2)
      YO2S=(UYFS/(2*L*OMEGA*ALPHA2))*BETA2*Y1S
C     PRINT*,'YO2=',YO2
      RHS=1E-5*((TERM1+TERM2)*CMPLX(X(3),X(5))+TERM3-TERM4)
C     PRINT*,'RHS=',RHS
      RHSR=REAL(RHS)
      RHSI=AIMAG(RHS)
      D(3)=X(4)
      D(4)=RHSR
      D(5)=X(6)
      D(6)=RHSI
      RHS2=(L*OMEGA*101.E3*UYF)/(8314.4*TAU*TAMB)
      RHSR2=REAL(RHS2)
      RHSI2=AIMAG(RHS2)
      D(7)=RHSR2
      D(8)=RHSI2
C     PRINT*,D(3),D(4),D(5),D(6),D(7),D(8)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
```

The following output correspond to these input parameters :

(i) Unsteady pressure at carbon surface = 150 dB =632.46 Pa

(ii) Unsteady temperature at carbon surface = 1.0 K

(iii) Frequency of oscillation = 100 cycles/second = 628.32 rad/se

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

VS FORTRAN VERSION 2 ENTERED.  18:30:31

**MAIN** END OF COMPILATION 1 ******

**FCN** END OF COMPILATION 2 ******

**RKINIT** END OF COMPILATION 3 ******

**NRKVSH** END OF COMPILATION 4 ******

VS FORTRAN VERSION 2 EXITED.   18:30:43

Execution begins...
TSURF =
?
1171.
 TAMB =
?
600.
Y1B =
?
0.0
Y2B =
?
0.0
Y3B =
?
0.1126
BOUNDARY LAYER THICKNESS =
?
5E-3
INPUT TSF
?
(1.,0.)
ENTER STEP SIZE :
?
0.1
THE RESULTS SHOWN BELOW PROVIDE THE VARIOUS DESIRED
VALUES FROM THE SURFACE OF THE CARBON (y=0) TO THE
BOUNDARY (y=1) IN STEPS OF 0.1.(NB . THE PRINTOUT
STARTS WITH y=0.1 AND GOES TO y=1.0 AND CONSEQUENTLY
THE VALUES AT THE CARBON SURFACE (y=0) ARE PRINTED

---------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.109346867
MASS FRACTION OF CO  = 0.239433423E-01
MASS FRACTION OF O2  = 0.193930157E-01
TEMPERATURE          =  1161.52759

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.142978145E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.909860987E-08)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MASS FRACTION OF O2  =(0.000000000E+00,0.519920462E-08)
TEMPERATURE          =(-0.643781424E-01,-0.136627108E-01)
MAGNITUDE OF TEMP.   =(0.658119321E-01,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.209123135,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.548891257E-03,0.000000000E+00)

-------------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.103954971
MASS FRACTION OF CO  = 0.169825777E-01
MASS FRACTION OF O2  = 0.272919685E-01
TEMPERATURE          =  1121.76123

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.711835355E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.452986377E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.258849298E-07)
TEMPERATURE          =(-1.12879848,-0.676032901E-01)
MAGNITUDE OF TEMP.   =(1.13082027,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.598181486E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.530099263E-03,0.000000000E+00)

-------------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.936344266E-01
MASS FRACTION OF CO  = 0.131581910E-01
MASS FRACTION OF O2  = 0.369831622E-01
TEMPERATURE          =  1065.49292

UNSTEADY VALUES

MASS FRACTION OF CO2 =(0.000000000E+00,-0.942404768E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.599712280E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.342692594E-07)
TEMPERATURE          =(-2.15951824,-0.181734502)
MAGNITUDE OF TEMP.   =(2.16715145,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.839572549E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.503509073E-03,0.000000000E+00)

-------------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.810781717E-01
MASS FRACTION OF CO  = 0.107565969E-01
MASS FRACTION OF O2  = 0.474873222E-01
TEMPERATURE          =  1001.73950

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.989469982E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.629663077E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.359807402E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

TEMPERATURE             =(-3.15334892,-0.378075838)
MAGNITUDE OF TEMP.      =(3.17593288,0.000000000E+00)
PHASE ANGLE OF TEMP.    =(0.119327009,0.000000000E+00)
VELOCITY IN Y-DIREC.    =(0.473381951E-03,0.000000000E+00)

-------------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.676598549E-01
MASS FRACTION OF CO  = 0.890355185E-02
MASS FRACTION OF O2  = 0.583049804E-01
TEMPERATURE          =  935.100098

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.957400630E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.609255153E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.348145832E-07)
TEMPERATURE          =(-4.11702156,-0.681847274)
MAGNITUDE OF TEMP.   =(4.17310047,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.164126873,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.441890676E-03,0.000000000E+00)

-------------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.539622158E-01
MASS FRACTION OF CO  = 0.722828860E-02
MASS FRACTION OF O2  = 0.692241788E-01
TEMPERATURE          =  867.524902

UNSTEADY VALUES

MASS FRACTION OF CO2 =(0.000000000E+00,-0.897239261E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.570970897E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.326268967E-07)
TEMPERATURE          =(-5.05352497,-1.12182426)
MAGNITUDE OF TEMP.   =(5.17654228,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.218446136,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.409957487E-03,0.000000000E+00)

-------------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.401908457E-01
MASS FRACTION OF CO  = 0.559986755E-02
MASS FRACTION OF O2  = 0.801702142E-01
TEMPERATURE          =  799.703857

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.828989641E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.527539115E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.301450775E-07)
TEMPERATURE          =(-5.95671940,-1.73051739)
```

```
FILE. CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MAGNITUDE OF TEMP.    =(6.20299816,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.282732546,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.377907883E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.264043733E-01
MASS FRACTION OF CO  = 0.398111716E-02
MASS FRACTION OF O2  = 0.911217332E-01
TEMPERATURE          =  731.831787

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.758924443E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.482952203E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.275972631E-07)
TEMPERATURE          =(-6.80986881,-2.54459858)
MAGNITUDE OF TEMP.   =(7.26975060,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.357598305,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.345834531E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.126156546E-01
MASS FRACTION OF CO  = 0.236377423E-02
MASS FRACTION OF O2  = 0.102074087
TEMPERATURE          =  663.951660

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.688560817E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.438175149E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.250385703E-07)
TEMPERATURE          =(-7.58434105,-3.60561275)
MAGNITUDE OF TEMP.   =(8.39777660,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.443776488,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.313756987E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 =-0.117323175E-02
MASS FRACTION OF CO  = 0.746542821E-03
MASS FRACTION OF O2  = 0.113026500
TEMPERATURE          =  596.072266

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.618167064E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.393379160E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.224788046E-07)
TEMPERATURE          =(-8.23637772,-4.96071911)
MAGNITUDE OF TEMP.   =(9.61491680,0.000000000E+00)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

PHASE ANGLE OF TEMP. =(0.542104363,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.281679910E-03,0.000000000E+00)

-----------------------------------------------------------
******************VALUES AT CARBON SURFACE*****************************
STEADY MASS FRACTION OF CO2 = 0.105689883
STEADY MASS FRACTION OF CO  = 0.366624892E-01
STEADY MASS FRACTION OF O2  = 0.147845633E-01
STEADY TEMPERATURE          =  1171.00000
-----------------------------------------------------------
UNSTEADY MASS FRACTION OF CO2     =(0.000000000E+00,0.853551683E-07)
UNSTEADY MASS FRACTION OF CO      =(0.000000000E+00,-0.543169634E-07)
UNSTEADY MASS FRACTION OF O2      =(0.000000000E+00,-0.310382582E-07)
UNSTEADY TEMPERATURE              =(1.00000000,0.000000000E+00)
UNSTEADY VELOCITY IN Y-DIRECTION =(0.553367659E-03,0.000000000E+00)
ADMITTANCE                        =(0.173801644E-03,0.000000000E+00)
***********************************************************************
```

The following output correspond to these input parameters :

(i) Unsteady pressure at carbon surface = 150 dB = 632.46 Pa

(ii) Unsteady temperature at carbon surface = 2.0 K

(iii) Frequency of oscillation = 100 cycles/second = 628.32 rad/sec

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1


VS FORTRAN VERSION 2 ENTERED.  18.33:26

**MAIN** END OF COMPILATION 1 ******

**FCN** END OF COMPILATION 2 ******

**RKINIT** END OF COMPILATION 3 ******

**NRKVSH** END OF COMPILATION 4 ******

VS FORTRAN VERSION 2 EXITED.   18:33:36

Execution begins...
TSURF =
?
1171.
 TAMB =
?
600.
Y1B =
?
0.0
Y2B =
?
0.0
Y3B =
?
0.1126
BOUNDARY LAYER THICKNESS =
?
5E-3
INPUT TSF
?
(2.,0.)
ENTER STEP SIZE
?
0.1
THE RESULTS SHOWN BELOW PROVIDE THE VARIOUS DESIRED
VALUES FROM THE SURFACE OF THE CARBON (y=0) TO THE
BOUNDARY (y=1) IN STEPS OF 0.1.(NB : THE PRINTOUT
STARTS WITH y=0.1 AND GOES TO y=1.0 AND CONSEQUENTLY
THE VALUES AT THE CARBON SURFACE (y=0) ARE PRINTED

---------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.109346867
MASS FRACTION OF CO  = 0.239433423E-01
MASS FRACTION OF O2  = 0.193930157E-01
TEMPERATURE          .=  1161.52759

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.285956361E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.181972233E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MASS FRACTION OF O2  =(0.000000000E+00,0.103984164E-07)
TEMPERATURE          =(-0.128784120,-0.755545124E-02)
MAGNITUDE OF TEMP.   =(0.129005551,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.586003959E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.109778321E-02,0.000000000E+00)

-----------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.103954971
MASS FRACTION OF CO  = 0.169825777E-01
MASS FRACTION OF O2  = 0.272919685E-01
TEMPERATURE          =  1121.76123

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.142367128E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.905972684E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.517698879E-07)
TEMPERATURE          =(-2.25808907,-0.569824502E-01)
MAGNITUDE OF TEMP.   =(2.25880718,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.252294540E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.106019899E-02,0.000000000E+00)

-----------------------------------------------------
STEADY VALUES .

MASS FRACTION OF CO2 = 0.936344266E-01
MASS FRACTION OF CO  = 0.131581910E-01
MASS FRACTION OF O2  = 0.369831622E-01
TEMPERATURE          =  1065.49292

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.188480954E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.119942456E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.685385544E-07)
TEMPERATURE          =(-4.32159901,-0.189391971)
MAGNITUDE OF TEMP.   =(4.32574463,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.437964872E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.100701861E-02,0.000000000E+00)

-----------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.810781717E-01
MASS FRACTION OF CO  = 0.107565969E-01
MASS FRACTION OF O2  = 0.474873222E-01
TEMPERATURE          =  1001.73950

UNSTEADY VALUES ·

MASS FRACTION OF CO2 =(0.000000000E+00,-0.197893996E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.125932559E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.719614377E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

TEMPERATURE            =(-6.31501293,-0.449188471)
MAGNITUDE OF TEMP.     =(6.33096695,0.000000000E+00)
PHASE ANGLE OF TEMP.   =(0.710105896E-01,0.000000000E+00)
VELOCITY IN Y-DIREC.   =(0.946763903E-03,0.000000000E+00)

-------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.676598549E-01
MASS FRACTION OF CO  = 0.890355185E-02
MASS FRACTION OF O2  = 0.583049804E-01
TEMPERATURE          =  935.100098

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.191480183E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.121851144E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.696292091E-07)
TEMPERATURE          =(-8.25497818,-0.886365652)
MAGNITUDE OF TEMP.   =(8.30242634,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.106963634,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.883781817E-03,0.000000000E+00)

-------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.539622158E-01
MASS FRACTION OF CO  = 0.722829880E-02
MASS FRACTION OF O2  = 0.692241788E-01
TEMPERATURE          =  867.524902

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.179447966E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.114194165E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.652538006E-07)
TEMPERATURE          =(-10.1520367,-1.55793953)
MAGNITUDE OF TEMP.   =(10.2708817,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.152272820,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.819915207E-03,0.000000000E+00)

-------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.401908457E-01
MASS FRACTION OF CO  = 0.559986755E-02
MASS FRACTION OF O2  = 0.801702142E-01
TEMPERATURE          =  799.703857

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.165797928E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.105507809E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.602901764E-07)
TEMPERATURE          =(-12.0001850,-2.52893829)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MAGNITUDE OF TEMP.   =(12.2637663,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.207702339,0.000000000E+00
VELOCITY IN Y-DIREC. =(0.755816000E-03,0.000000000E+ ,)

-----------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.264043733E-01
MASS FRACTION OF CO  = 0.398111716E-02
MASS FRACTION OF O2  = 0.911217332E-01
TEMPERATURE          =  731.831787

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.151784718E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.965903268E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.551944872E-07)
TEMPERATURE          =(-13.7743521,-3.87364388)
MAGNITUDE OF TEMP.   =(14.3086643,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.274141014,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.691668596E-03,0.000000000E+00)

-----------------------------------------------------
STEADY VALUES .

MASS FRACTION OF CO2 = 0.126156546E-01
MASS FRACTION OF CO  = 0.236377423E-02
MASS FRACTION OF O2  = 0.102074087
TEMPERATURE          =  663.951660

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.137712050E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.876349873E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.500771371E-07)
TEMPERATURE          =(-15.4283562,-5.67735195)
MAGNITUDE OF TEMP.   =(16.4397736,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.352603436,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.627513742E-03,0.000000000E+00)

-----------------------------------------------------
STEADY VALUES

MASS FRACTION OF CO2 =-0.117323175E-02
MASS FRACTION OF CO  = 0.746542821E-03
MASS FRACTION OF O2  = 0.113026500
TEMPERATURE          =  596.072266

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.123633356E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.786757823E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.449575950E-07)
TEMPERATURE          =(-16.8891907,-8.03843403)
MAGNITUDE OF TEMP.   =(18.7045746,0.000000000E+00)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

PHASE ANGLE OF TEMP. =(0.444224298,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.563359587E-03,0.000000000E+00)

---------------------------------------------------------
******************VALUES AT CARBON SURFACE***************************
STEADY MASS FRACTION OF CO2 = 0.105689883
STEADY MASS FRACTION OF CO  = 0.366624892E-01
STEADY MASS FRACTION OF O2  = 0.147845633E-01
STEADY TEMPERATURE          =  1171.00000
---------------------------------------------------------
UNSTEADY MASS FRACTION OF CO2    =(0.000000000E+00,0.170710337E-06)
UNSTEADY MASS FRACTION OF CO     =(0.000000000E+00,-0.108633799E-06)
UNSTEADY MASS FRACTION OF O2     =(0.000000000E+00,-0.620764808E-07)
UNSTEADY TEMPERATURE             =(2.00000000,0.000000000E+00)
UNSTEADY VELOCITY IN Y-DIRECTION =(0.110673555E-02,0.000000000E+00)
ADMITTANCE                       =(0.347603345E-03,0.000000000E+00)
**********************************************************************
```

The following output corresponds to these input parameters :

(i) Unsteady pressure at carbon surface = 150 dB = 632.46 Pa

(ii) Unsteady temperature at carbon surface = 2.0 K

(iii) Frequency of oscillation = 80 cycles/second = 502.65 rad/sec

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

VS FORTRAN VERSION 2 ENTERED.  18:38:56

**MAIN** END OF COMPILATION 1 ******

**FCN** END OF COMPILATION 2 ******

**RKINIT** END OF COMPILATION 3 ******

**NRKVSH** END OF COMPILATION 4 ******

VS FORTRAN VERSION 2 EXITED.   18:39:05

Execution begins...
TSURF =
?
1171.
 TAMB =
?
600.
Y1B =
?
0.0
Y2B =
?
0.0
Y3B =
?
0.1126
BOUNDARY LAYER THICKNESS =
?
5E-3
INPUT TSF
?
(2.,0.)
ENTER STEP SIZE :
?
0.1
THE RESULTS SHOWN BELOW PROVIDE THE VARIOUS DESIRED
VALUES FROM THE SURFACE OF THE CARBON (y=0) TO THE
BOUNDARY (y=1) IN STEPS OF 0.1.(NB . THE PRINTOUT
STARTS WITH y=0.1 AND GOES TO y=1.0 AND CONSEQUENTLY
THE VALUES AT THE CARBON SURFACE (y=0) ARE PRINTED

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.109346867
MASS FRACTION OF CO  = 0.239433423E-01
MASS FRACTION OF O2  = 0.193930157E-01
TEMPERATURE          =  1161.52759

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.357449963E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.227468107E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MASS FRACTION OF O2  =(0.000000000E+00,0.129981821E-07)
TEMPERATURE          =(-0.128787756,-0.604429096E-02)
MAGNITUDE OF TEMP.   =(0.128929496,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.468977690E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.109778321E-02,0.000000000E+00)

-----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.103954971
MASS FRACTION OF CO  = 0.169825777E-01
MASS FRACTION OF O2  = 0.272919685E-01
TEMPERATURE          =  1121.76123

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.177961113E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.113248007E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.647131060E-07)
TEMPERATURE          =(-2.25817204,-0.455855355E-01)
MAGNITUDE OF TEMP.   =(2.25863171,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.201841742E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.106017899E-02,0.000000000E+00)

-----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.936344266E-01
MASS FRACTION OF CO  = 0.131581910E-01
MASS FRACTION OF O2  = 0.369831622E-01
TEMPERATURE          =  1065.49292

UNSTEADY VALUES

MASS FRACTION OF CO2 =(0.000000000E+00,-0.235604205E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.149929917E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.856742304E-07)
TEMPERATURE          =(-4.32221887,-0.151513075)
MAGNITUDE OF TEMP.   =(4.32487106,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.350403003E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.100701861E-02,0.000000000E+00)

-----------------------------------------------------------
STEADY VALUES ·

MASS FRACTION OF CO2 = 0.810781717E-01
MASS FRACTION OF CO  = 0.107565969E-01
MASS FRACTION OF O2  = 0.474873222E-01
TEMPERATURE          =  1001.73950

UNSTEADY VALUES

MASS FRACTION OF CO2 =(0.000000000E+00,-0.247370622E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.157417617E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.899529482E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

TEMPERATURE            =(-6.31767845,-0.359363139)
MAGNITUDE OF TEMP.     =(6.32788944,0.000000000E+00)
PHASE ANGLE OF TEMP.   =(0.568209216E-01,0.000000000E+00)
VELOCITY IN Y-DIREC.   =(0.946763903E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.676598549E-01
MASS FRACTION OF CO  = 0.890355185E-02
MASS FRACTION OF O2  = 0.583049804E-01
TEMPERATURE          =  935.100098

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.239353312E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.152315693E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.870375629E-07)
TEMPERATURE          =(-8.26340961,-0.709168494)
MAGNITUDE OF TEMP.   =(8.29378414,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.856105685E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.883781817E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES .

MASS FRACTION OF CO2 = 0.539622158E-01
MASS FRACTION OF CO  = 0.722828880E-02
MASS FRACTION OF O2  = 0.692241788E-01
TEMPERATURE          =  867.524902

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.224312714E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.142744454E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.815682597E-07)
TEMPERATURE          =(-10.1740265,-1.24666309)
MAGNITUDE OF TEMP.   =(10.2501202,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.121926069,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.819915207E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.401908457E-01
MASS FRACTION OF CO  = 0.559986755E-02
MASS FRACTION OF O2  = 0.801702142E-01
TEMPERATURE          =  799.703857

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.207249911E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.131886375E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.753636300E-07)
TEMPERATURE          =(-12.0504208,-2.02417564)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MAGNITUDE OF TEMP.   =(12.2192430,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.166421831,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.755816000E-03,0.000000000E+00)

--------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.264043733E-01
MASS FRACTION OF CO  = 0.398111716E-02
MASS FRACTION OF O2  = 0.911217332E-01
TEMPERATURE          =  731.831787

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.189733271E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.120739458E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.689939270E-07)
TEMPERATURE          =(-13.8786068,-3.10182762)
MAGNITUDE OF TEMP.   =(14.2210073,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.219883442,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.691668596E-03,0.000000000E-00)

--------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.126156546E-01
MASS FRACTION OF CO  = 0.236377423E-02
MASS FRACTION OF O2  = 0.102074087
TEMPERATURE          =  663.951660

UNSTEADY VALUES .

MASS FRACTION OF CO2 =(0.000000000E+C0,-0.172142165E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.109545113E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.625971666E-07)
TEMPERATURE          =(-15.6296406,-4.54932880)
MAGNITUDE OF TEMP.   =(16.2782593,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.283244669,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.627513742E-03,0.000000000E+00

--------------------------------------------------------
STEADY VALUES .

MASS FRACTION OF CO2 =-0.117323175E-02
MASS FRACTION OF CO  = 0.746542821E-03
MASS FRACTION OF O2  = 0.113026500
TEMPERATURE          =  596.072266

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.154543500E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.983459358E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.561976847E-07)
TEMPERATURE          =(-17.2568054,-6.44833660)
MAGNITUDE OF TEMP.   =(18.4222107,0.000000000E+00)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

PHASE ANGLE OF TEMP. =(0.357603371,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.563359587E-03,0.000000000E+00)

----------------------------------------------------------
******************VALUES AT CARBON SURFACE***************************
STEADY MASS FRACTION OF CO2 = 0.105689883
STEADY MASS FRACTION OF CO  = 0.366624892E-01
STEADY MASS FRACTION OF O2  = 0.147845633E-01
STEADY TEMPERATURE          =  1171.00000
----------------------------------------------------------
UNSTEADY MASS FRACTION OF CO2     =(0.000000000E+00,0.213390535E-06)
UNSTEADY MASS FRACTION OF CO      =(0.000000000E+00,-0.135794039E-06)
UNSTEADY MASS FRACTION OF O2      =(0.000000000E+00,-0.775966100E-07)
UNSTEADY TEMPERATURE              =(2.00000000,0.000000000E+00)
UNSTEADY VELOCITY IN Y-DIRECTION =(0.110673555E-02,0.000000000E+00)
ADMITTANCE                        =(0.347603345E-03,0.000000000E+00)
**********************************************************************
```

The following output corresponds to these input parameters :

(i) Unsteady pressure at carbon surface = 140 dB = 200 Pa

(ii) Unsteady temperature at carbon surface = 2.0 K

(iii) Frequency of oscillation = 100 cycles/second = 628.32 rad/sec

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

VS FORTRAN VERSION 2 ENTERED.  18:41:39

**MAIN** END OF COMPILATION 1 ******

**FCN** END OF COMPILATION 2 ******

**RKINIT** END OF COMPILATION 3 ******

**NRKVSH** END OF COMPILATION 4 ******

VS FORTRAN VERSION 2 EXITED.   18:41.48

Execution begins...
TSURF =
?
1171.
 TAMB =
?
600.
Y1B =
?
0.0
Y2B =
?
0.0
Y3B =
?
0.1126
BOUNDARY LAYER THICKNESS =
?
5E-3
INPUT TSF
?
(2.,0.)
ENTER STEP SIZE :
?
0.1
THE RESULTS SHOWN BELOW PROVIDE THE VARIOUS DESIRED
VALUES FROM THE SURFACE OF THE CARBON (y=0) TO THE
BOUNDARY (y=1) IN STEPS OF 0.1.(NB : THE PRINTOUT
STARTS WITH y=0.1 AND GOES TO y=1.0 AND CONSEQUENTLY
THE VALUES AT THE CARBON SURFACE (y=0) ARE PRINTED

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.109346867
MASS FRACTION OF CO  = 0.239433423E-01
MASS FRACTION OF O2  = 0.193930157E-01
TEMPERATURE          =  1161.52759

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.285956361E-07)
MASS FRACTION OF CO  =(0.000000000E+00,0.181972233E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MASS FRACTION OF O2  =(0.000000000E+00,0.103984164E-07)
TEMPERATURE          =(-0.128808439,0.596276298E-02)
MAGNITUDE OF TEMP.   =(0.128946364,0.000000000E+00)
PHASE ANGLE OF TEMP. =(-0.462586842E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.109778321E-02,0.000000000E+00)

-----------------------------------------------------------
STEADY VALUES .

MASS FRACTION OF CO2 = 0.103954971
MASS FRACTION OF CO  = 0.169825777E-01
MASS FRACTION OF O2  = 0.272919685E-01
TEMPERATURE          =  1121.76123

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.142367128E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.905972684E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.517698879E-07)
TEMPERATURE          =(-2.25844002,-0.349476049E-02)
MAGNITUDE OF TEMP.   =(2.25844288,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.154742110E-02,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.106019899E-02,0.000000000E+00)

-----------------------------------------------------------
STEADY VALUES

MASS FRACTION OF CO2 = 0.936344266E-01
MASS FRACTION OF CO  = 0.131581910E-01
MASS FRACTION OF O2  = 0.369831622E-01
TEMPERATURE          =  1065.49292

UNSTEADY VALUES

MASS FRACTION OF CO2 =(0.000000000E+00,-0.188480954E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.119942456E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.685385544E-07)
TEMPERATURE          =(-4.32337666,-0.703628659E-01)
MAGNITUDE OF TEMP.   =(4.32394695,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.162735395E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.100701861E-02,0.000000000E+00)

-----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.810781717E-01
MASS FRACTION OF CO  = 0.107565969E-01
MASS FRACTION OF O2  = 0.474873222E-01
TEMPERATURE          =  1001.73950

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.197893996E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.125932559E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.719614377E-07)
```

```
FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

TEMPERATURE              =(-6.32073498,-0.239296019)
MAGNITUDE OF TEMP.       =(6.32526112,0.000000000E+00)
PHASE ANGLE OF TEMP.  =(0.378408171E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.946763903E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.676598549E-01
MASS FRACTION OF CO  = 0.890355185E-02
MASS FRACTION OF O2  = 0.583049804E-01
TEMPERATURE          =  935.100098

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.191480183E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.121851144E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.696292091E-07)
TEMPERATURE          =(-8.26933956,-0.559982836)
MAGNITUDE OF TEMP.   =(8.28827763,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.676146746E-01,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.883781817E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.539622158E-01
MASS FRACTION OF CO  = 0.722828880E-02
MASS FRACTION OF O2  = 0.692241788E-01
TEMPERATURE          =  867.524902

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.179447966E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.114194165E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.652538006E-07)
TEMPERATURE          =(-10.1828547,-1.08907413)
MAGNITUDE OF TEMP.   =(10.2409277,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.106546700,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.819915207E-03,0.000000000E+00)

----------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.401908457E-01
MASS FRACTION OF CO  = 0.559986755E-02
MASS FRACTION OF O2  = 0.801702142E-01
TEMPERATURE          =  799.703857

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.165797928E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.105507809E-06)
MASS FRACTION OF O2  =(0.000000000E+00,0.602901764E-07)
TEMPERATURE          =(-12.0595684,-1.89160347)
```

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FILE. CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

MAGNITUDE OF TEMP.   =(12.2070198,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.155587256,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.755816000E-03,0.000000000E+00)

--------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.264043733E-01
MASS FRACTION OF CO  = 0.398111716E-02
MASS FRACTION OF O2  = 0.911217332E-01
TEMPERATURE          =  731.831787

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.151784718E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.965903268E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.551944872E-07)
TEMPERATURE          =(-13.8801527,-3.04249287)
MAGNITUDE OF TEMP.   =(14.2096939,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.215784550,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.691668596E-03,0.000000000E+00)

--------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 = 0.126156546E-01
MASS FRACTION OF CO  = 0.236377423E-02
MASS FRACTION OF O2  = 0.102074087
TEMPERATURE          =  663.951660

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.137712050E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.876349873E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.500771371E-07)
TEMPERATURE          =(-15.6060019,-4.62854958)
MAGNITUDE OF TEMP.   =(16.2779236,0.000000000E+00)
PHASE ANGLE OF TEMP. =(0.268323343,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.627513742E-03,0.000000000E+00)

--------------------------------------------------------
STEADY VALUES :

MASS FRACTION OF CO2 =-0.117323175E-02
MASS FRACTION OF CO  = 0.746542821E-03
MASS FRACTION OF O2  = 0.113026500
TEMPERATURE          =  596.072266

UNSTEADY VALUES :

MASS FRACTION OF CO2 =(0.000000000E+00,-0.123633356E-06)
MASS FRACTION OF CO  =(0.000000000E+00,0.786757823E-07)
MASS FRACTION OF O2  =(0.000000000E+00,0.449575950E-07)
TEMPERATURE          =(-17.1740265,-6.75091839)
MAGNITUDE OF TEMP.   =(18.4532318,0.000000000E+00)
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FILE: CONSOLE  PRINTOUT A   ERAU VM/CMS REL 5.1

PHASE ANGLE OF TEMP. =(0.374534309,0.000000000E+00)
VELOCITY IN Y-DIREC. =(0.563359587E-03,0.000000000E+00)

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*******************VALUES AT CARBON SURFACE***************************
STEADY MASS FRACTION OF CO2 = 0.105689883
STEADY MASS FRACTION OF CO  = 0.366624892E-01
STEADY MASS FRACTION OF O2  = 0.147845633E-01
STEADY TEMPERATURE          =  1171.00000
----------------------------------------------------------
UNSTEADY MASS FRACTION OF CO2     =(0.000000000E+00,0.170710337E-06)
UNSTEADY MASS FRACTION OF CO      =(0.000000000E+00,-0.108633799E-06)
UNSTEADY MASS FRACTION OF O2      =(0.000000000E+00,-0.620764808E-07)
UNSTEADY TEMPERATURE              =(2.00000000,0.000000000E+00)
UNSTEADY VELOCITY IN Y-DIRECTION =(0.110673555E-02,0.000000000E+00)
ADMITTANCE                        =(0.109922606E-02,0.000000000E+00)
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